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Real-time spectrum occupancy monitoring using a probabilistic model

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ABSTRACT

The scarcity of the radio spectrum has motivated a search for more optimal and efficient spectrum management methods. One of these methods is spectrum sharing, which multiplies the number of devices that can use this resource without causing harmful interference to licensees. Spectrum sharing requires spectrum scanning to gain awareness of the spectrum occupancy patterns and decide how to allocate access to this resource. This process has been traditionally done by sensing the channel to determine its state, occupied or empty, and then using frequentist inference to estimate the channel occupancy. However, frequentist inference does not handle uncertainty and does not take into account the probabilities of false alarm and detection when estimating the channel occupancy rate. On the other hand, Bayesian inference can handle uncertainty by considering the impact of these parameters on spectrum sensing results. Additionally, it is possible to include previous knowledge into the construction of Bayesian models to learn and make decision under uncertainty. In this paper, we propose a spectrum scanning method, Bayesian inference, to estimate the channel occupancy rate. One advantage of this method is that it takes into consideration the probabilities of false alarm and detection of the spectrum sensor. This feature makes the estimation of the channel occupancy rate more accurate.

1. Introduction

The radio spectrum is a limited natural resource that must be managed properly to enable new services and applications. The continuous increase in mobile applications, wireless systems, and subscribers has created a demand for this resource and motivated the search for new strategies for optimizing and taking the greatest advantage of the radio spectrum [1]. One of this strategies is spectrum sharing, a scheme wherein several devices can use the same portion of the spectrum either simultaneously or in turns. The goal of spectrum sharing is optimizing the radio spectrum by exploiting empty or underutilized channels. Underutilized channels are referred to those licensed and unlicensed channels that are intermittently utilized in time. As long as no harmful interference is caused to the licensees, also known as primary users, spectrum sharing is a promising technology that can enable many new wireless services.

One of the requirements of spectrum sharing is spectrum awareness [2,3]. Spectrum awareness is accomplished through monitoring the spectrum which involves two stages: (1) sensing the channels of interest to determine if they are idle or occupied and (2) delivering the results either at the instant the measurement takes place or after having collected several measurements. The first stage provides real-time information on the status of a channel, while the latter reveals short or long term occupancy trends. Several spectrum monitoring surveys have been conducted worldwide at different locations, covering both wide frequency ranges and specific licensed bands, including those in the U.S. [4,5], New Zealand [6], Singapore [7], Germany [8], Spain [9], Poland [9,10], Malaysia [11], South Africa [12], and Finland [13]. However, there are certain limitations associated with these surveys. First, all these surveys use energy detection with a fixed threshold. The energy detection sensing technique operates by comparing power measurements with a threshold, determined based on the noise power. This noise power is random, which causes energy detection sensors to have high rate of false alarms and misdetections [14]. Second, these surveys used the frequentist inference technique to estimate the channel occupancy rate; this technique has difficulties to handle nuisance parameters, such as the probabilities of detection and false alarm of the spectrum sensor, and other sources of uncertainty.

Since the occupancy rate of a channel varies randomly and several sources of uncertainty affect its measurement, spectrum monitoring should be approached using probabilistic models. In this paper, therefore, we propose a spectrum monitoring method that includes a probabilistic model, a Bayesian network, which

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takes into consideration the probability of detection and false alarm of the sensing technique. The proposed model can be extended to include other random variables that might affect the spectrum occupancy measurements.

In the proposed method, we use a spectrum sensing technique that is based on the autocorrelation of the received samples [15], which unlike the energy detection technique, requires no previous knowledge of either the noise power level or the characteristics of the transmitted signals [16]. There are several ways to analyze the autocorrelation of signals to detect when a radio frequency channel is occupied [16–19]. In [16], a spectrum sensing method based on received signal samples covariance matrix was proposed in which two test statistics were calculated from the covariance matrix and compared to make a decision on the presence of the primary user. The authors of [19] proposed two spectrum sensing methods based on eigenvalues of the covariance matrix calculated from received signals at secondary users. They showed that two ratios of maximum to minimum eigenvalues and average to minimum eigenvalues can be used to detect the presence of the primary user. In this work, we use the Euclidean distance between the autocorrelation of the signal and a reference line as an appropriate metric to detect the occupancy of a channel [15]. This spectrum sensing method is also compared to the energy detection method and autocorrelation based technique, which specifically employs the value of the autocorrelation function at the first lag [20]. In addition, we compare the proposed Bayesian method with the frequentist inference method regarding its capability to estimate the channel occupancy rate.

The paper is organized as follows: Section 2 explains and compares the frequentist and Bayesian inference techniques; Section 3 explains the proposed Bayesian model; Section 4 explains the methodology used to obtain the results; and Section 5 discusses the simulation and experimental results. Finally, Section 6 offers our conclusions from the research effort.

2. Inference techniques

Channel occupancy is a random variable; hence, it should be described in terms of its probability distribution. To determine whether the channel is empty or occupied, a spectrum sensing device takes samples from the channel. The efficiency of the spectrum sensor depends on the probabilities of detection and false alarm and the level of occupancy of the channel. Although channel occupancy is a hidden variable, its probability distribution can be inferred from samples taken by the spectrum sensor.

There are two inference techniques to use for estimating the probability of a random variable: 1) Frequentist technique that infers the probability based on the frequency of observations; and 2) Bayesian technique that infers the probability based on previous knowledge/observations and current observation/evidence.

2.1. Frequentist inference

When using the frequentist inference method, the probability of the occurrence of an event is the limit of its frequency, given a large number of trials [21]. In this approach, the sample space is defined as the set of all possible outcomes of a random experiment wherein an event X is a subset of the sample space under consideration. The frequency of occurrence of this event is a measure of its probability $P(X)$, defined in Eq. (1). In a total of N_T trials, where N_X is the number of occurrences of the event, the probability or the frequency of occurrence can be given as follows

$$P(X) = N_X / N_T \tag{1}$$

As the number of trials increases, $P(X)$ gets closer to the actual probability.

The frequentist approach has been employed for several spectrum occupancy monitoring surveys [4–13]. For example, in [22], the spectrum sensing technique proposed in [15] was applied to scan a set of channels to estimate their occupancy rates using frequentist statistics. The authors of [23] performed the spectrum occupancy measurement and analysis in Beijing, China, in 2012. In that survey, a spectrum analyzer in conjunction with a broadband antenna was used to record the data. Several channels were scanned multiple times, and then channel occupancy was computed as

$$\textit{Average spectrum occupancy} = \frac{N_o}{N} \tag{2}$$

where N_o is the number of observations indicating the channel is occupied, and N is the total number of observations. The higher the number of observations, the more precise the result is.

2.2. Bayesian inference

Bayesian inference is based on Bayes's rule in which we can identify the following elements: 1) a hypothesis space H, composed of all the possible models; 2) some observation data or evidence d; and 3) a posterior probability $P(h|d)$, which is calculated from the *a priori* probability $P(h)$ and the likelihood $P(d|h)$ [24,25]. The prior probability $P(h)$ measures the plausibility of each causal hypothesis h, but without taking into consideration the observation data d. The likelihood $P(d|h)$ measures the likeliness of observing the data while considering the hypothesis to be true. The Bayes's rule defines the posterior probability as the product of the prior probability and the likelihood normalized by the marginal likelihood $P(d)$ [26]. Since normalizing is not a requirement, the marginal likelihood $P(d)$ in the Eq. (3) can be ignored. The Bayesian rule is thus given by

$$P(h|d) = \frac{P(d|h)P(h)}{P(d)} \tag{3}$$

The advantage of Bayesian inference is its ability to use background knowledge and experience. The Bayesian method is useful in situations where we need to infer the probability distribution of a random variable, in this case channel occupancy, based on prior knowledge and right after observing the evidence. On the other hand, the frequentist method is more suitable for estimating probability distributions after collecting a large set of data [27].

The Bayesian inference is performed over a Bayesian network, a directed acyclic graph, wherein the vertices represent random and deterministic variables and the edges represent the causal relations between those variables [24,28]. The next section describes the proposed Bayesian network for inferring the probability distribution of the channel occupancy rate.

3. The Bayesian model for scanning the radio spectrum

In a previous work [29], a simplified Bayesian model was proposed, consisting of only deterministic variables and measured variables. In this paper, we propose a new improved Bayesian model for monitoring the radio spectrum. In order to implement uncertainty handling, random variables are added to the previous model. A random variable for received power is added to the model from which the signal-to-noise ratio (SNR) is estimated [30,31]. In addition, the values of probabilities of detection and false alarm corresponding to the estimated SNR and the spectrum sensing technique are obtained. The contribution of this model is the inclusion of the probabilities of detection and false alarm to produce more accurate estimates of channel occupancy probability. In other words, we present an improved method based on Bayesian