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Traffic-Aware Green Cognitive Radio

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ABSTRACT

Cognitive Radio Network (CRN) has emerged as an effective solution to the spectrum under-utilization problem, by providing secondary users (SUs) an opportunistic access to the unoccupied frequency bands of primary users (PUs). Most of the current research on CRN are based on the assumption that the SU always has a large amount of data to transmit. This leads to the objective of SU throughput maximization with a constraint on the allowable interference to the PU. However, in many of the practical scenarios, the data arrival process of the SU closely follows an ON–OFF traffic model, and thus the usual throughput optimization framework may no longer be suitable. In this paper, we propose an intelligent data scheduling strategy which minimizes the average transmission power of the SU while maintaining the transmission delay to be sufficiently small. The data scheduling problem has been formulated as a finite horizon Markov Decision Process (MDP) with an appropriate cost function. Dynamic programming approach has been adopted to arrive at an optimal solution. Our findings show that the average transmitted power for our proposed approach can be as small as 36.5% of the power required for usual throughput maximization technique with insignificant increase in average delay.

1. Introduction

Cognitive Radio Network (CRN) facilitates better spectrum utilization by allowing Secondary Users (SUs) to transmit their data via unoccupied frequency bands of Primary Users (PUs), while maintaining the interference to PUs below a certain threshold. In particular, SU senses the presence of PU by continuously monitoring the dynamic radio environment and exploits the spectrum holes opportunistically. The most well studied indicator of performance for CRN has traditionally been the throughput of the SU. For example, there have been various works on obtaining the optimal sensing time [1], facilitating cooperative sensing [2], multiband joint detection [3], multi-antenna driven spectrum sensing [4] etc. In all these works, optimizing the throughput of the SU was the primary objective.

However, throughput optimization is justified under the assumption that the radio is always saturated i.e. the SU always has sufficiently large amount of data to transmit. But, such an assumption is not valid in many practical scenarios, such as, internet applications where the SU traffic is generally modelled as bursty ON–OFF streams of data [5–7]. For such applications, it is natural to ask whether the commonly used definition of performance metric needs to be revised. Based on the concavity of the power-rate function, one can conclude that the power required to transmit a large amount of data over a short period of time (large data rate) is significantly higher than the power required to transmit the same amount of data over a longer period (small data rate). Thus, if one has the luxury to distribute the traffic over a longer duration, significant reduction of transmission power may be achieved. The idea of exploiting the concavity of the rate-power function to achieve energy efficiency, has already been explored in the literature, though not in the context of CRN [8,9]. In these papers, the authors seek to minimize the energy expenditure by judiciously delaying the data transmission over a wireless channel.

In this paper, we exploit the log-concavity of the rate-power function to achieve energy efficiency in the context of ON–OFF traffic model in CRN. Note that for an ON–OFF stream of data, arrivals occur only during the ON periods. Thus, instead of serving all the arrivals within the ON period (which is the case in throughput maximization), if an SU utilizes some portion of the OFF period for transmission purpose, there will be a significant improvement in energy efficiency. This proposition becomes the basic intuition behind our 'green' cognitive radio.

The idea of energy efficient cognitive radio is not new in the literature, though the term 'energy efficiency' is interpreted differently under different context. For example, the power minimization technique in multi-input multi-output (MIMO) CRN

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is driven by the objective to identify a power allocation scheme which minimizes the total transmitted power of the network while satisfying individual rate demands (or equivalently, signal-to-interference plus noise ratio) of the SU terminals [10,11]. While this method might turn out to be suitable for constant bit rate traffic, a new approach needs to be adopted for bursty data arrivals. Similar concepts can also be found in cooperative relay networks where a set of cognitive radios act as intermediate relays between a predefined source and destination [12,13]. Incorporation of circuit power consumption into the optimization framework defines another dimension of current research [14–16]. In [14,15] maximization of energy efficiency (defined as effective number of bits transmitted per unit energy) is of primary concern. On the other hand, [16] focuses on minimization of the total energy consumption while transmitting a single data packet. To the best of our knowledge, none of the existing power minimization techniques address and thus exploit the bursty nature of the SU traffic.

With this motivation, we introduce an analytical framework towards devising an energy efficient data transmission strategy for an SU. Note that the problem thus defined demands an anticipation of the future at every decision epoch. Thus, a 'green' transmission strategy should not only be concerned about the current 'state' of the system, but also looks forward through an infinite horizon of future possibilities. Hence, the problem fits well into the category of Markov Decision Process (MDP). Although the chosen traffic model is non-Markovian, we have shown that a certain definition of system states leads to the formulation of Markov chains. In particular, we are required to find a transmission strategy which minimizes the average transmitted power of the SU while ensuring that the interference to the PU remains below a specified level.

However, a reduction in the transmission power comes at the cost of enhanced transmission delay (or equivalently, an increment in the average queue length) of the SU. Therefore, a certain Quality-of-Service (QoS) for the SU can be ensured by continuously monitoring its current queue length. This can be achieved by designing an appropriate cost function for the MDP. The brief design philosophy is as follows: whenever the queue length is within a desired threshold, we concentrate on minimizing the transmission power. Therefore, in this case, the cost function simply becomes the transmitted power. However, when the queue length exceeds the threshold, we modify the cost function as a weighted sum of the transmitted power and the excess queue-length. The relative weights assigned to these variables determine the trade-off between the power-gain and the delay experienced by the SU.

Interestingly, the underlying solution conjoins elements across different layers. For example, here the SU is required to have knowledge about traffic distribution from the Media Access Control (MAC) layer to decide a transmission power at the Physical (PHY) layer. Thus the process to obtain an optimal solution to this problem might be seen as a cross layer design approach. The details of this solution will be discussed in the forthcoming sections. We conclude the introduction by summarizing our key contributions:

(i) We assume a realistic traffic model for the SU, namely bursty data arrivals, which, to the best of our knowledge, has not been analysed in any of the existing literatures.
(ii) We have proposed and built on the idea that the void spaces in OFF periods can be leveraged to reschedule the data transmission over a longer duration, leading to an enhanced performance in terms of power usage.
(iii) We have shown that, despite the traffic model being non-Markovian, it is possible to construct a Markov chain by appropriately defining the system states. This formulation makes our analysis tractable.
(iv) By defining a suitable cost function, we have achieved substantial power gain over the conventional method of rate maximization at the cost of relaxed delay tolerance. The function parameters can be suitably chosen in order to find out the best power-delay trade-off fit for the system in consideration.

The rest of the paper is organized as follows: we have introduced the system model in Section 2 which leads to the definition of system states and policy in Section 3, followed by the formation of Markov chain in Section 4. An analytical formulation of the problem is presented in Section 5. Section 6 presents the results and simulations while Section 7 provides concluding remarks.

2. System model

We consider a single channel Cognitive Radio network consisting of a single Secondary User (SU) and a single Primary User (PU). The occupancy of the channel by the PU is assumed to be an independent and slotted random process and the SU is allowed to utilize the spectrum only in the absence of the PU. Thus, in order to identify a temporal spectrum hole, the SU is required to carry out spectrum sensing at the beginning of each slot. If the outcome of the sensing process is positive i.e. the PU is detected to be present, the SU does not transmit any data. However, if the PU is detected to be absent, the SU decides to serve some of its stored messages in the buffer based on the available traffic information. Details of this detection process is elaborated in the following subsection.

2.1. Energy detection based spectrum sensing

The spectrum sensing problem at the receiver of the SU can be expressed as a binary hypothesis testing problem:

$$\mathcal{H}_0 : x(n) = w(n), \quad n = 0, 1, \dots, N_0 - 1$$
$$\mathcal{H}_1 : x(n) = s(n) + w(n), \quad n = 0, 1, \dots, N_0 - 1$$

where $x(n)$ is the (sampled) received signal, $s(n)$ is the signal transmitted by the PU and $w(n)$ indicates zero mean AWG noise with known variance σ_n^2. The hypotheses $\mathcal{H}_0$ and $\mathcal{H}_1$ correspond to the absence and the presence of the PU respectively. In absence of any prior information about the PU signal, spectrum sensing simply turns out to be an energy detection method, in which the SU compares the cumulative energy of the first N_0 samples of $x(n)$ with a certain threshold η. The test statistics for this method thus turns out to be:

$$\mathcal{T} = \sum_{n=0}^{N_0-1} |x(n)|^2 \quad (1)$$

Based on this test statistics, the SU decides for a particular hypothesis according to the following decision rule:

$$\mathcal{D} = \begin{cases} \mathcal{H}_0 & \text{if } \mathcal{T} \le \eta \\ \mathcal{H}_1 & \text{if } \mathcal{T} > \eta \end{cases}$$

We assume $\{s(n)\}, n = 0, 1, \dots, N_0 - 1$ to be i.i.d. zero mean Gaussian random variables with variance σ_s^2 [17]. From (1), the distribution of $\mathcal{T}$ can easily be derived as:

$$\mathcal{T} = \begin{cases} \sigma_n^2 \chi^2 & \text{if } \mathcal{H}_0 \text{ is true} \\ (\sigma_n^2 + \sigma_s^2)\chi^2 & \text{if } \mathcal{H}_1 \text{ is true} \end{cases}$$

where χ^2 is distributed according to the central chi squared distribution with N_0 degrees of freedom. Probability of false alarm imposed by this detection method is thus:

$$p_f(\eta) = P(\mathcal{T} > \eta | \mathcal{H}_0) = \frac{\Gamma\left(\frac{N_0}{2}, \frac{\eta}{2\sigma_n^2}\right)}{\Gamma\left(\frac{N_0}{2}\right)} \quad (2)$$