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ENERGY EFFICIENT DESIGN IN COGNITIVE RADIO NETWORKS WITH DELAY BOUNDS

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ABSTRACT

Energy Efficiency is one of the crucial parameters in the design of modern wireless and other futuristic communication systems. Cognitive Radio is a highly evolving physical layer technology which is known for its environment-aware operations, self-configurability and learning. Energy Efficient design is inevitably a matter of addressing various trade-offs. In this paper, we formulate an optimization frame work for maximizing the energy efficiency by jointly optimizing the sensing duration and transmission duration. Also, the delay bounds are carefully designed in such a way that they are not beyond the desired values. Numerical and simulation results indicate that the proposed methodology resulted in higher energy efficiency compared to many existing methods. Apart from boosting up the achievable energy efficiency, this work was successful in bringing the delay bounds with in the desired range.

Key words: Energy Efficiency, Cognitive Radios, Delay bounds, Optimization Problem, Sensing Duration, Transmission Duration, Non-convex problem

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1. INTRODUCTION

Cognitive Radios have emerged as a brilliant and promising technology for 5G and other next generation wireless communications. They were initially proposed as a method for mitigating the spectral congestion problem. Spectral congestion or spectral inadequacy was the immediate consequence of the overwhelmingly increasing number of connected devices, users and services. The concept of “Cognitive Radios” were initially proposed by Joseph Mitola [1] in his seminal thesis work. It is an intelligent radio, which is capable of taking decisions and acting accordingly based on the environmental conditions.

While connected devices and services were growing in enormous numbers, the carbon gas emissions due to them were found to be creating far reaching effects on the environmental equilibrium of the earth. Not only that, the strong electro-magnetic radiations from these smart devices posed serious health hazards to all living beings including human beings. Reduced battery life is another big challenge that the new generation wireless systems are facing. Putting it all together, there is a need for energy aware designs in the area of wireless communications.

Cognitive Radios are anticipated to support energy efficient designs due to its self-awareness, re-configurability, self-learning, spectral efficiency and dynamic spectral allocation features. Dynamic spectrum allocation of Cognitive Radios stem from their ability to spot vacant licensed bands which are currently un-occupied. This is accomplished through the task called spectrum sensing [2-4]. Through spectrum sensing the cognitive radio transceivers spot the licensed user activity in the frequency bands of interest. The licensed users are also called Primary Users (PU) in cognitive radio terminologies. The frequency bands of interest are selected on the relative PU activity on a statistical basis. For instance, the analog TV bands which were licensed during its inception stage became useless as TV transmissions moved on to the digital domain. The un-licensed users who are allowed to use the licensed bands under the absence of the PUs are called the Secondary Users (SUs).

The rest of the paper is organized as follows. Section 2 presents an overview of the spectrum sensing process, which is the most crucial and preliminary task of the CR transceiver. Section 3 covers the comprehensive literature survey on spectrum sensing and energy efficiency. Section 4 is dedicated to problem formulation. Numerical and simulation results are covered in section 5 and the paper concludes in section 6.

2. SPECTRUM SENSING PROCESS

Spectrum sensing is the preliminary task carried out by CR transceivers to ascertain whether the licensed bands are vacant or not. CRs continuously monitor the PU activity by proper detection methods. Depending on the detection criterion used, sensing methods are generally classified as i) Energy-based Spectrum sensing ii) Matched Filter spectrum sensing iii) Cyclo-stationary based spectrum sensing and iv) Eigen value based spectrum sensing. The sensing performance is dependent on various parameters like multi-path fading, shadowing effects, noise-uncertainty etc. Therefore, in-order to know the performance characteristics of sensing, a standard curve called ROC (Receiver Operating Characteristics) is constructed. Similarly, the performance of the detector is specified on the basis of Probability of Detection P_d and Probability of False Alarm P_{fa}. According to WRAN (IEEE 802.22) standards, the value of P_d should not be less than 0.9 and the value of P_{fa} should not exceed 0.1.

2.1. Spectrum Sensing Methods

Sensing is posed as a detection problem based on hypothesis testing. The received signal can be represented as :

$$y(t) = \begin{cases} n(t) & H_0 \\ x(t) + n(t) & H_1 \end{cases}$$

where $n(t)$ is the Additive White Gaussian Noise (AWGN), H_0 and H_1 represent the hypothesis related to the absence and presence of PUs respectively. The aim of the spectrum sensing is to arrive at a conclusion as to whether the PU is active in the given band or not.

2.1.1. Energy Detection

It is the most common method of spectrum sensing. The test statistics of the energy detector is defined as follows:

$$Y = \frac{1}{N}\sum_{i=1}^{N}|x(t)|^2$$

The decision is based on a comparison with the pre-defined threshold. The advantage of the energy detector is that the process is blind in that, it does not require any prior information about the PU signal. But, there exists an SNR wall for the performance of the energy detector to be optimum. This means that, under low SNR conditions, the performance of the energy detector is sub-standard.

2.1.2. Matched Filter Detection

If there is any possibility of knowing the PU information, then the optimal detection method is matched filtering [7], which performs a correlation operation between the primary signal with the received signal to detect the PU activity. The advantage of matched filtering detector is that it requires short sensing time to achieve good detection performance. The disadvantage is that, it needs to know the PU transmit signal which may not be known at the SUs most of the times.

2.1.3. Cyclostationary Detection

Cyclostationary utilizes the cyclostationary feature of the signals for spectrum sensing [5,6]. This is possible through analyzing the cyclic autocorrelation function (CAF) of the received signal. Feature detector can distinguish noise from the PU signals and can be used for detecting weak signals at a very low SNR region, where the energy detection and matched filtering detection are not applicable.

2.2. Spectrum Sensing and Energy Efficiency

As far as energy efficiency is concerned, spectrum sensing is a matter of trade-off. A typical cognitive time frame is depicted in figure. A typical cognitive frame consists of two intervals.

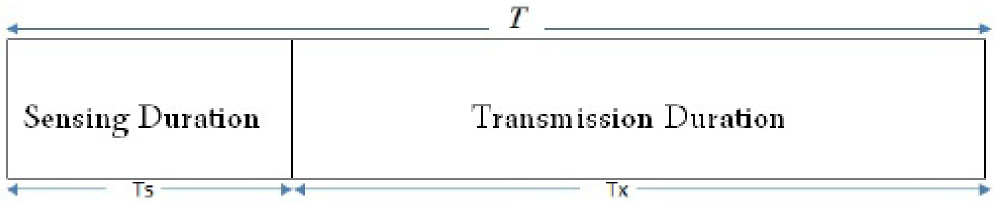


Figure 1 A typical Cognitive Frame

During the first interval, sensing is done to arrive at a decision whether the PU is active in the given band. If the decision is that the PU is absent, the during the second interval, the CR transmitter starts transmitting till the beginning of the next frame. The first time interval constitutes the sensing interval and the second interval is known as the transmission interval. While adapting sensing duration and transmission duration for boosting energy efficiency in a sensing based system, there is an interesting trade-off. In the first place, even though increasing the sensing duration will result in higher values of probability of detection which increases the sensing accuracy, there might not be a subsequent performance in terms of energy efficiency. Increased sensing accuracy results in better utilization of the vacant spectrum and therefore, the chances of successful transmission are more. However, with increased sensing duration, the transmission duration becomes less and therefore this could result in reduced throughput. Therefore unilateral increase in the sensing duration is not definitely a solution for energy efficiency enhancement.

The second possibility arises from decreasing the sensing duration for larger transmission duration. It is obvious that even though the transmission duration has increased, there will not be a significant increase in the achievable throughput. This is because, on decreasing the sensing duration, the sensing accuracy decreases, which affect the optimal utilization of spectral vacancies. Therefore, it is clear that there exists a unique sensing duration, transmission duration pair for the optimal energy efficiency and this need not be the parameter pair for maximum throughput.

2.3. Delay Overhead in Spectrum Sensing

Due to sensing process, there will an associated delay. Most of the present generation networks are delay sensitive networks, which means that delay in transmission must brought under tolerable limits. While optimizing for the maximum energy efficiency, there are possibilities by which the optimal values of sensing duration is higher than the maximum permissible delay. In such cases, delay must be brought under stricter bounds in order to ensure satisfactory delay performance

3. LITERATURE SURVEY

Authors in papers [8]-[10] have studied EE in CR wireless networks under different scenarios related to sensing duration/transmission duration optimization. In [8], the authors propose an EE maximization method on the basis of designing sensing and transmission duration as required by a CR frame. The selection of sensing time and transmission duration is a matter of trade-off as detailed in contribution [11]. It is clear that the sensing duration should be long enough to get precise sensing results. However, too long a sensing duration cannot be entertained since this will result in loss of throughput. Articles [11] and [12] discuss the maximization of secondary throughput by trading off sensing duration and sensing time. By the same token, the trade-off between sensing duration and transmission duration from the EE perspective too was investigated [10]-[13]. Different from the works so far, we attempt to formulate a joint sensing duration-transmission duration based optimization problem for EE maximization by examining three different scenarios.

4. SYSTEM MODEL

The CR system under consideration is a single antenna, single carrier sensing based system. The model is depicted in the Fig. 2. The secondary channels between secondary transmitter to secondary receiver are indicated as h_{ss} and to the primary receiver as. h_{sp}. The medium between the primary transmitter and the primary receiver are shown as g_{pp} and g_{ps}. The channels are assumed to be Rayleigh faded. Noise is Additive White Gaussian noise (AWGN) with zero mean and variance σ^2. Besides, the channel is assumed to be block faded, ie, the channel characteristics do not change with in one frame. Each data frame of CR user is of duration T units of time, which can be represented as $T = \tau_s + \tau_x$, where τ_s represents the sensing duration, τ_x represents the transmission duration.

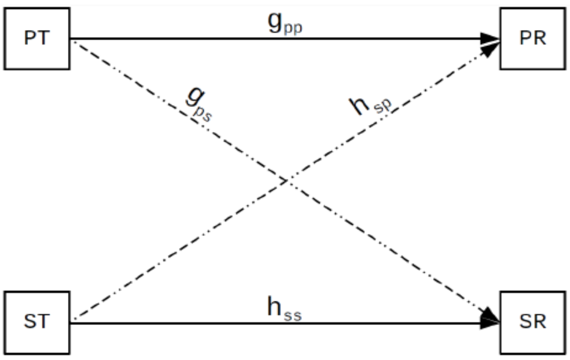


Figure 2 Model of the Channel

4.1. Delay Modeling

In this section, we model the delay in the spectrum-sensing process. As per the system model, the SU is engaged in the periodic monitoring of the PU spectral bands to know its activity. Re-transmission of the SU data, under necessary conditions adds to the QoS of the secondary system, but at the cost of additional delay overhead. Two types of delay are identified. They are :

- Delay due to busy periods of the PU and sensing overhead
- Delay caused by data re-transmission

In our work, delay due to data re-transmission is not taken into consideration because retransmission is mostly higher-layer protocol based and therefore will not result in significant margins from physical layer designs. We analyze the delay due to spectrum sensing. It can be easily identified that the SU transmission delay occurs under the following three scenarios:

- Delay due to spectrum sensing($\boldsymbol{D_1(\tau_s)}$): This delay is an inevitable delay in any sensing-based CR network. In this case, $\boldsymbol{D_1(\tau_s) = \tau_s}$ itself.
- Delay due to false alarm $(\boldsymbol{D_2(\tau_s)})$: The delay due to false alarm can be represented as $\boldsymbol{D_2\,(\tau_s) = (P(H_0) + P_{fa})\,\tau_s + (T - \tau_s)}$
- Delay due to Correct Detection $(\boldsymbol{D_3(\tau_s)})$: The delay due to correct detection can be represented as $\boldsymbol{D_3(\tau_s) = (P(H_1) + P_{fa})\tau_s + T - \tau_s}$.

The average time delay in transmission involved is therefore given by

$$\boldsymbol{D(\tau_s) = \tau_s + \left(P(H_0) + P_{fa}\right)\tau_s + (T - \tau_s) + (P(H_1) + P_{fa})\tau_s + \tau_s}$$

5. PROBLEM FORMULATION

According to [12], the average throughput of the CR users is given by $\boldsymbol{\widehat{R} = \frac{\tau_x}{T}\left(1 - P_{fa}\right)P(H_0)R_0}$, where $\boldsymbol{R_0}$ is the achievable through put under ideal sensing conditions and $\boldsymbol{\widehat{R}}$ is the achievable through put in the case with sensing defects. Energy efficiency is defined as the ratio of average through put to the total transmitted power, which is given by:

$$\eta = \frac{\frac{\tau_x}{T}\left(1 - P_{fa}\right)P(H_0)R_0}{P_c(\tau_x + \tau_s) + \tau_x P_t}$$

where the denominator represents energy consumed in a frame, with $\boldsymbol{P_c}$ representing the circuit power and $\boldsymbol{P_t}$ representing the total transmit power.

Thus, the maximization problem can be represented as

$$\max_{\tau_s,\tau_x} \eta = \frac{\frac{\tau_x}{T}\left(1 - P_{fa}\right)P(H_0)R_0}{P_c(\tau_x + \tau_s) + \tau_x P_t}$$

subject to the constraints :

$$\text{C1:} \quad \tau_s \geq \frac{Q^{-1}(P_{famax} - A)}{B}$$

$$\text{C2:} \quad \tau_x + \tau_s \leq T$$

$$\text{C3:} \; P_{fa} \leq P_{famax}$$

$$\text{C4:} \quad D(\tau) = D_{th}$$

In the first constraint, the sensing duration is purposefully kept above a particular value given in the right hand side of the equation. Here A and B denotes constant values as far as the probability of false alarm is concerned. Therefore the sensing duration has to be brought above a particular value so as to ensure that the probability of false alarm is not going beyond the P_{famax}, which is fixed to be 0.1. Similarly, the last constraint is regarding the delay threshold that can be tolerated during the sensing process and D_{th} is the maximum possible delay for delay critical applications. In the above problem, the objective function is the ratio of the achieved throughput to the energy consumed. It is obvious that the problem is non-convex, due to its fractional nature and further due to the association between the variables involved in optimization. In the proposed work, we perform optimization with the help of binary search methods, since the functions follow a uni-modal behavior. The following section discusses the results.

6. RESULTS AND DISCUSSION

The figure below (Fig. 3) is plot of Energy w.r.t. sensing duration for different values of transmission durations. The curve follows an uni-modal nature, which shows that there exists a unique value of sensing duration for which the energy efficiency is maximum.

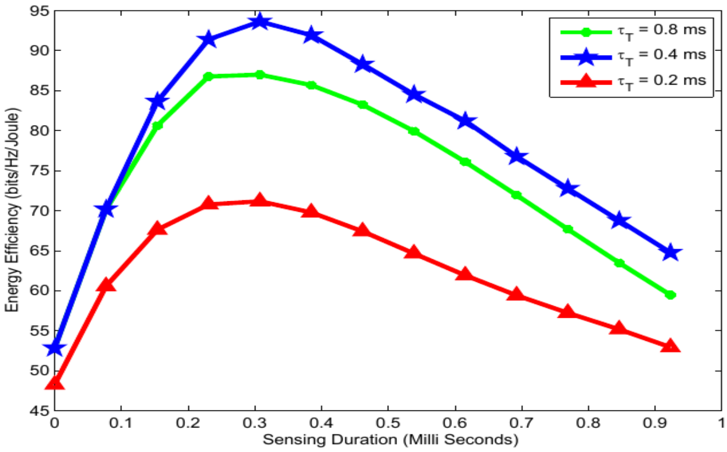
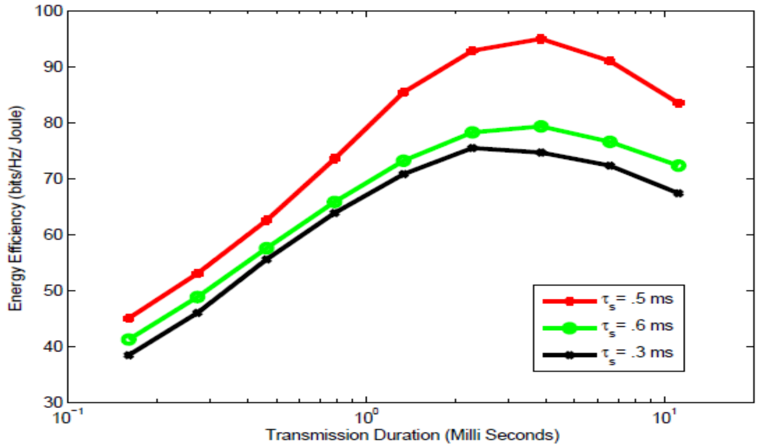
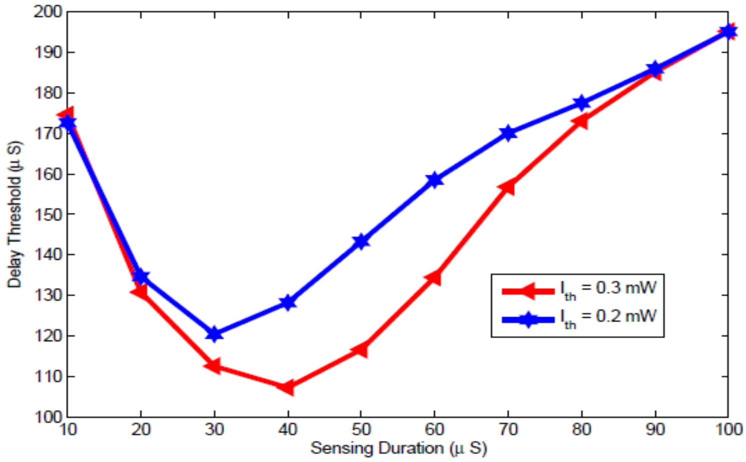


Figure 3 Energy Efficiency vs. Sensing Duration

Figure 4 shows the variation of Energy Efficiency w.r.t. transmission duration. As is observed, energy efficiency is a non-convex curve w.r.t transmission duration and is uni-modal. This also proves that there exists a unique value for the transmission duration . In figure 5, the delay characteristics of the system is plotted. The Delay threshold vs. Energy Efficiency is plotted in this figure.





7. CONCLUSIONS

Energy Efficiency has become a parameter of prime importance in conventional as well as many futuristic networks. In the case of CR networks, energy efficient design can be performed by adjusting sensing duration and transmission duration in optimal manner. Also, this involves the trade-off between delay overhead and energy efficiency. This delay tradeoff involved in the design has been addressed in this work. The numerical and simulation results show this method outperforms various other existing methods in terms of achievable energy efficiency and the delay bound performance obtained.

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