Sensing Window Length Optimization in Low-SNR Regime

Liaoyuan Zeng

Abstract For non-coherent detection based cognitive radio (CR), the required length of the spectrum sensing window is inversely proportional to the primary user's (PUs) signal strength. When a CR system's transmission period is fixed, the length of the CR's transmission window can be inadequate to fully utilize the white space if the corresponding PUs operate in low-SNR regime. We propose a sensing window optimization algorithm in this paper aiming at improving the spectral efficiency of the cognitive Ultra Wideband (UWB) radio system. The proposed algorithm can find the optimal tradeoff between the sensing window length and the desired detection probabilities for the UWB based CR system in low-SNR regime. Compared with the conventional sensing algorithms in which the sensing window is fixed, the proposed algorithm can significantly increase the length of the CR-UWB's transmission window so as to use the available spectrum more efficiently while guaranteeing the PUs' operation.

Keywords Spectrum sensing window • Cognitive radio • Ultra wideband • Low-SNR regime

1 Introduction

To implement cognitive radio (CR) [1], one of the ideal candidate technologies is Ultra Wideband (UWB) [2]. UWB operates in 3.1–10.6 GHz with an extremely low power spectrum density (PSD) − 41.3 dBm/MHz [3], which facilitates the underlay spectrum sharing technique to co-exist with the primary users (PUs) that operate within the UWB's wide spectrum band [4]. Generally, to protect the PUs from being harmfully interfered, the CR-UWB's transmit power can be decreased

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to a level that is significantly lower than the UWB’s regular PSD, which can result in considerably low spectral efficiency for the CR-UWB. By using orthogonal frequency division multiplexing (OFDM) in UWB, the CR-UWB system can adaptively adjust the transmit power of the OFDM subcarriers according to the spectrum sensing results within the interested spectrum segments which are overlapped with the PU’s operating bands. The spectral efficiency of the overlapped spectrum is critical to the overall spectral efficiency of the CR-UWB system and is dependent on the performance of the spectrum sensing algorithm.

We assume that the characteristics of the PUs signal are unknown to the CR-UWB. Hence, the non-coherent detection based energy detection technique can be chosen to verify the availability of the overlapped spectrum due to energy detector’s use of the Fourier transform (FT) function which is a key in the OFDM based UWB system [5]. To determine the PUs’ presence successfully, the length of the CR-UWB’s spectrum sensing window shall be adequate which is dependent on the PUs signal’s signal to noise ratio (SNR) received at the CR-UWB and the thresholds of the probability of detection/false alarm. Since the length of the sensing window is roughly inversely proportional to the PUs’ signal strength, for a CR-UWB system in which the duration of spectrum access is fixed, the length of the CR-UWB’s spectrum sensing window can have a critical impact on the finally overall spectral efficiency in a way that the length of the sensing window determines the length of the transmission window, in which an excessive sensing window fulfilling the PUs protection requirement can produce a shortened transmission window which will limit CR-UWB’s use of the overlapped spectrum. When PUs operate in a low-SNR regime, i.e., the SNR detected at the CR-UWB’s receiver is extremely low, the time required to successfully detect the PUs can be excessively long, which can lead to a considerably short transmission window which in turn can result in a unacceptable spectral efficiency.

In this paper, we propose a spectrum sensing optimization algorithm in low-SNR regime, aiming at improving the CR-UWB’s spectral efficiency by finding the tradeoff optimality of the spectrum sensing window length and the spectrum sensing performance. The sensing performance is characterized by the probability of false alarm (PFA) and the probability of detection (PD). By computing the optimal sensing window length, the proportion between the CR-UWB’s transmission window length to the duration of the spectrum access can be maximized while guaranteeing the PUs operation, which can facilitate the fully use of the overlapped spectrum by incorporating a high efficient transmission scheme.

The remainder of the paper is organized as follows. Section 2 gives a brief overview of the current spectrum sensing window optimization methods. Section 3 presents the spectrum sensing model and the formulation of the spectrum sensing window optimization problem. The proposed sensing window optimization algorithm is demonstrated in Sect. 4. Then, the numerical results are presented in Sect. 5. Finally, Sect. 6 gives a conclusion to the paper.

2 Literature Review

Stotas et al. and Peh et al. laid the fundamental work for dealing with the spectrum sensing window optimization problem in [6, 7], respectively. The Lagrange dual optimization method was used by Stotas et al. in [6] to optimize the power distribution mechanism and the spectrum sensing scheme by tuning the sensing window length adaptively to optimize the throughput of the CR system. In Stotas's algorithm, the iterations required for identifying the multiple Lagrange multipliers' values is considerable. In [8], Zou et al. used the Taylor approximation to find the relationship of the PFA and PD. The authors then minimized the CR's overall outage probability through optimizing the sensing window length using linear programming technique [9]. However, the performance of Zou's algorithm in low PU SNR regime will be degraded considerably because of the required sensing window length would be excessive.

3 System Model

In the work, we model the spectrum sensing window optimization problem as a convex optimization problem, in which the decision variable is the CR-UWB's sensing window length, and the main constraints consist of the thresholds of CR-UWB's PD and PFA. We deal with the formulated optimization problem by using linear programming. To validate our algorithms performance in term of spectral efficiency enhancement, we combine the proposed sensing window length optimization algorithm with the water-filling based transmission scheme proposed in [10]. We assume the use of the overlay spectrum sharing scheme and the application of an ideal notch filter. Hence, the sideband interference from the CR-UWB system to the PUs can be neglected.

Since the objective of the CR-UWB's spectrum sensing window length is to improve the overall spectral efficiency by increasing the spectral efficiency of the overlapped spectrum, the problem of optimizing the spectrum sensing window length denoted as **P1** can be mapped into the optimization problem of maximizing the overlapped spectrum's spectral efficiency. Thus, **P1** is expressed as:

$$\begin{aligned} \mathbf{P1}\ \arg\max_{\tau_s} S_e = \frac{\beta}{T_{op}} S(1-P_f)(1-P(\mathcal{H}_1)) \quad (1) \\ \text{s.t.}: \bar{P}_d \le P_d \le 1 \\ 0 \le P_f \le \bar{P}_f \\ \tau_s \ge \frac{2}{\gamma_p^2 f_s}\left(Q^{-1}(\bar{P}_f) - Q^{-1}(\bar{P}_d)\right)^2, \end{aligned}$$

where S_e denotes the spectral efficiency of the overlapped spectrum when the CR-UWB maintains the access to the spectrum while the corresponding PUs cease operating temporarily, S represents the spectral efficiency when the CR-UWB has full access to the overlapped spectrum where no PU is surrounded, $\beta = \frac{(T_{op}-\tau_s)}{T_{op}}$ denotes the ratio between the CR-UWB's transmission window length and the fixed duration of the CR-UWB's access to the overlapped spectrum, T_{op} is the pre-defined length of the spectrum access window, τ_s represents the sensing window length which is determined by the PU's SNR, UWB's sampling frequency and the target PFA/PD, P_f and $\bar{P}_f$ represents the actual PFA and the target PFA respectively, P_d and $\bar{P}_d$ represents the real-time PD and the target PD respectively, and $P(\mathcal{H}_1)$ shows the probability that a PU activates within T_{op}.

We assume that the probability that a PU is activated during T_{op} follows a Poisson process and is expressed as $P(\mathcal{H}_1) = p(x;\lambda t) = \frac{e^{-\lambda t}(\lambda t)^x}{x!}$ [11], where x denotes the expected number of occurrences of PU's activations during the period of t which in our system model $t = T_{op}$.

For the constraints expressed in **P1**, γ_p represents the received PU signals SNR at the CR-UWB receiver, f_s denotes the UWB's sampling rate. Furthermore, $Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} exp\left(-\frac{y^2}{2}\right)dy$ is the one-dimensional Gaussian Q-function [12].

By observing that both S and $P(\mathcal{H}_1)$ are independent of τ_s, we can transform the optimization problem shown in **P1** into **P2** which is simpler to tackle as

$$\textbf{P2}\ arg\ \max_{\tau_s} F_r(\tau_s) = \beta\left[1 - Q\left(\frac{Q^{-1}(P_d)\sqrt{2(2\gamma_p + N)} + \gamma_p}{\sqrt{2N}}\right)\right], \tag{2}$$

where $N = \tau_s f_s$ denotes the number of spectrum sensing samples of CR-UWB's energy detector, and P_f, P_d and τ_s are related by [1]

$$P_f = Q\left(\frac{Q^{-1}(P_d)\sqrt{2(2\gamma_p + N)} + \gamma_p}{\sqrt{2N}}\right) \tag{3}$$

For simplicity and without loss of generality, we assume that there exists a single CR link within the CR-UWB network whose infrastructure is in distributed manner, and there are multiple PUs in the CR-UWB's network and the PUs' operating bandwidth is overlapped with the CR-UWB's. Overlay spectrum sharing is assumed, which indicates that the CR-UWB can access to the overlapped spectrum if and only if the energy detection result shows that the PUs are temporarily absent within the overlapped spectrum.

4 Sensing Window Length Optimization

To show the impact of the variation of the spectrum sensing window length on the CR-UWB's spectral efficiency and that there exists an optimal tradeoff between the sensing window length and the target PD and PFA, we compute the spectral efficiency of the CR-UWB in the overlapped spectrum as a function of the spectrum sensing window length which is measured in μs, as shown in Fig. 1.

At the CR-UWB's receiver, when the PUs' signal strength lies in the low-SNR regime, we observe that the spectral efficiency of the CR-UWB grows exponentially with the increase of τ_s and reaches a peak level when the spectrum sensing window is tuned to a certain value. As the value of τ_s grows beyond the optimal value, the CR-UWB's spectral efficiency decreases monotonically because the transmission window size, $T_{op} - \tau_s$, is shortened. Figure 1 numerically verifies that there exist an optimal τ_s under specific target $\bar{P}_d$, $\bar{P}_f$ and γ_p values.

To compute the optimal spectrum sensing window length for CR-UWB spectral efficiency enhancement under the constrains of $\bar{P}_f$ and $\bar{P}_d$, we use linear programming to calculate the optimized value of τ_s by computing the root for $f_r(\tau_s) = \frac{dF_r(\tau_s)}{d\tau_s} = 0$, where

$$f_r(\tau_s) = -\frac{1}{T_{txop}} - \left[Q'(\tau_s) - \frac{1}{T}(Q(f(\tau_s)) + Q'(f(\tau_s)))\right] = 0, \quad (4)$$

where $f(\tau_s)$ represents a function of τ_s and can be expressed as

$$f(\tau_s) = \frac{Q^{-1}(P_d)\sqrt{2(2\gamma_p + \tau_s f_s)} + \gamma_p}{\sqrt{2\tau_s f_s}} \quad (5)$$

and the $f(\tau_s)'$s first order differentiation is

$$f'(\tau_s) = \frac{Q^{-1}(P_d)f_s}{2\sqrt{(2\gamma_p + \tau_s f_s)\tau_s f_s}} - \frac{\sqrt{2}f_s(Q^{-1}(P_d)\sqrt{(4\gamma_p + 2\tau_s f_s)} + \gamma_p)}{4(\tau_s f_s)^{3/2}} \quad (6)$$

Nevertheless, computing the optimal τ_s in closed form is complex. Hence, exhaustive search method is used to approximately find the optimal spectrum sensing window length.

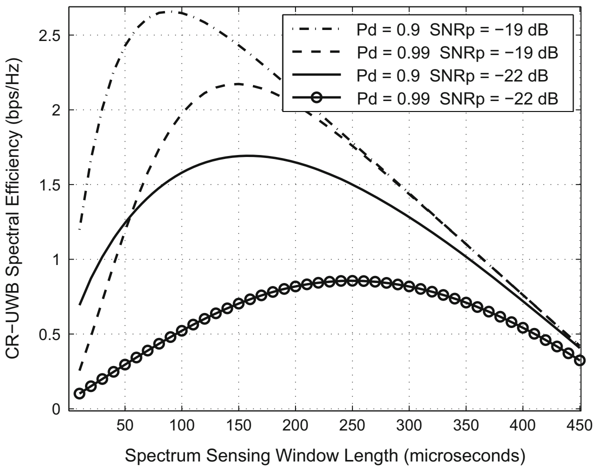

Fig. 1 The spectral efficiency as a function of the spectrum sensing window length

5 Numerical Simulation

In our work, the numerical simulation is implemented within a channel model that is previously specified in the UWB system [3]. The detected spectrum hole is used by an water-filling based algorithm [10] where the parameter settings can be referred to. Furthermore, for the PUs, λ is set to 1,000 per second to represent the random occupance of the PUs in the overlapped spectrum, and the target PD is set to 0.99.

We compare the spectral efficiency achieved by the fixed sensing window length based spectrum sensing method with the proposed sensing window length optimization algorithm, as shown in Fig. 2. It is seen that the proposed algorithm can obviously enhance the CR-UWB's spectral efficiency, especially when the PUs operate in low SNR regime. For instance, the corresponding spectral efficiency achieved by the traditional sensing method approaches zero when the value of γ_p decreases below -19 dB, while the CR-UWBs spectral efficiency achieved by the proposed sensing algorithm is profoundly higher. The spectral efficiency performance of the proposed algorithm is acceptable even when the PUs' SNR decreases below -25 dB. Furthermore, with the increase of the value of γ_p, the two lines gap shrinks in an exponential manner. As a comparison, when the PUs operate in normal or high-SNR regime (e.g., -10 dB), the gap becomes minor because a large value of γ_p can lead to a minor τ_s for a pre-defined threshold of $\bar{P}_f$ and $\bar{P}_d$.

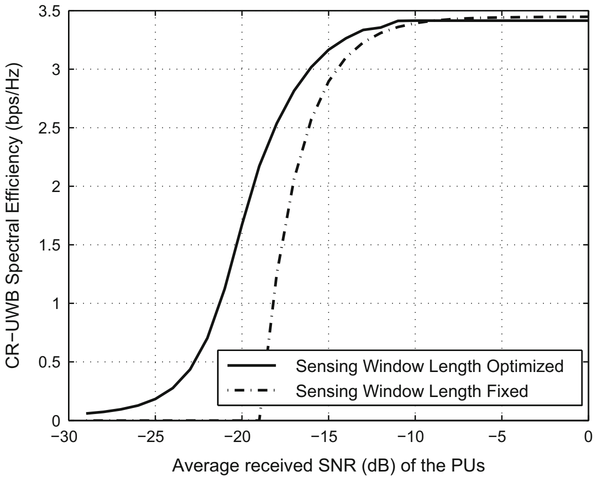

Fig. 2 The peak CR-UWB's spectral efficiency as a function of the PU's SNR received at the CR-UWB's receiver

6 Conclusion

To improve the overall spectral efficiency of the OFDM UWB based CR system when the corresponding PUs' operating power is extremely low, we proposed a novel spectrum sensing window optimization algorithm for the energy detection based CR-UWB system to find the optimal tradeoff between the detection probability and the length of the spectrum sensing window. We showed that our algorithm can identify the optimal length of the sensing window length through numerical method constrained by the target PD and PFA and then significantly prolong the transmission window when the duration of the CR-UWB's access to the overlapped spectrum is fixed. By integrating the spectral sensing window optimization algorithm with the existing spectrum management algorithm, the overall spectral efficiency of the CR-UWB was verified to be significantly increased compared with the traditional window length fixed sensing algorithm, especially in PU's low-SNR regime.

References

1. Mitola III J (1999) Cognitive radio for flexible mobile multimedia communications. In: Proceedings IEEE MoMuC, San Diego, pp 3–10
2. Porcino D, Walter, H (2003) Ultra-wideband radio technology: potential and challenges ahead. IEEE Comm Mag 41:66–74
3. Yang L, Giannakis GB (2004) Ultra-wideband communications: an idea whose time has come. IEEE Signal Process Mag 21:26–54
4. Akyildiz IF, Lee WY, Vuran MC (2006) NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey. Comput Netw 50:2127–2159

5. Digham FF, Alouini MS, Simon MK (2007) On the energy detection of unknown signals over fading channels. IEEE Trans Comm 55:21–24
6. Stotas S, Nallanathan A (2011) Optimal sensing time and power allocation in multiband cognitive radio networks. IEEE Trans Comm 59:226–235
7. Peh ECY, Liang YC, Guan YL (2009) Optimization of cooperative sensing in cognitive radio networks: a sensing-throughput tradeoff view. IEEE Trans Veh Technol 58:5294–5299
8. Zou Y, Yao YD, Zheng B (2010) Outage probability analysis of cognitive transmissions: impact of spectrum sensing overhead. IEEE Trans Wireless Comm 9:2676–2688
9. Palomar DP, Cioffi JM, Miguel AL (2003) Joint Tx-Rx beamforming design for multicarrier MIMO channels: a unified framework for convex optimization. IEEE Trans Signal Process 51:2381–2401
10. Zeng LY, McGrath S, Cano E (2009) Rate maximization for multiband OFDM ultra wideband systems using adaptive power and bit loading algorithm. In: Proceedings IARIA AICT, Venice, 369–374
11. Huang S, Liu X, Ding Z (2008) Opportunistic spectrum access in cognitive radio networks. In: Proceedings IEEE INFOCOM, Phoenix 1427–1435
12. Vogel K, Risken H (1989) Determination of quasiprobability distributions in terms of probability distributions for the rotated quadrature phase. Phys Rev 40:2847–2849

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