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Cognitive ultra wideband radio spectrum sensing window length optimization algorithm

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Abstract

A critical objective of cognitive radio (CR) system is to enhance the spectrum efficiency, and one of the key factors that can determine the spectrum efficiency is the system spectrum sensing performance with respect to sensing window length. For non-coherent detection-based sensing technique, the length of the sensing window required to meet the detection criteria is inversely proportional to the detected signal-to-noise ratio (SNR) of the primary users (PUs). This fact may result in an inadequate use of the white or gray space for the conventional CR system whose transmission and sensing window length are both fixed because a high detected PUs SNR can lead to an excessive long fixed sensing window which occupies the potential CR transmission opportunities while a low received PUs SNR can result in an insufficient sensing window length which degrades the CR detection criteria. In this paper, to improve the spectrum efficiency compared with the fixed sensing/transmission window length-based CR system, we propose an adaptive spectrum sensing window length optimization algorithm. We design the algorithm based on the ultra wideband (UWB) system which is an ideal candidate for the implementation of the CR technology. Based on the analysis of the CR-UWB's spectrum sensing technique in terms of the factors such as spectrum efficiency, spectrum sensing length, PUs SNR, detection criteria etc., we formulate the optimization problem into a convex problem, which enables the proposed algorithm to find the optimal trade-off with low computational complexity between the sensing window length and the desired detection probabilities for the CR-UWB system. Compared with the conventional fixed length spectrum sensing techniques, the proposed algorithm is verified to be able to adapt the length of the CR-UWB's transmission window according to the PUs SNR to optimize the use of the available spectrum while guaranteeing the PUs from being interfered.

Keywords: Cognitive radio; Ultra wideband; Spectrum sensing

Introduction

For cognitive radio (CR) [1], ultra wideband (UWB) can be used as an implementation technology [2]. UWB operates in 3.1 to 10.6 GHz with an extremely low power spectrum density (PSD) of -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]. Figure 1 illustrates the band overlap between the UWB system and the incumbent wireless systems such as wireless LAN [5]. Generally, to protect the PUs from being harmfully interfered, the CR-UWB's

transmit power can be decreased to a level that is significantly lower than the UWB's regular PSD, which can result in considerably low spectral efficiency.

By using orthogonal frequency division multiplexing (OFDM) [6], as shown in Figure 2, the UWB system can adaptively adjust the transmit power of the OFDM subcarriers according to the spectrum sensing results within the interested spectrum segments [7]. Figure 2 shows the band allocation scheme in the OFDM-based UWB system. The UWB's operating band is divided into band groups (BGs), each of which contains two or three subbands (SBs), and each SB consists of a series of mutually orthogonal subcarriers, which facilitates the design of dynamic spectrum access (DSA)-based methods. The spectral efficiency of the overlapped spectrum is critical to the overall spectral efficiency of the CR-UWB system and

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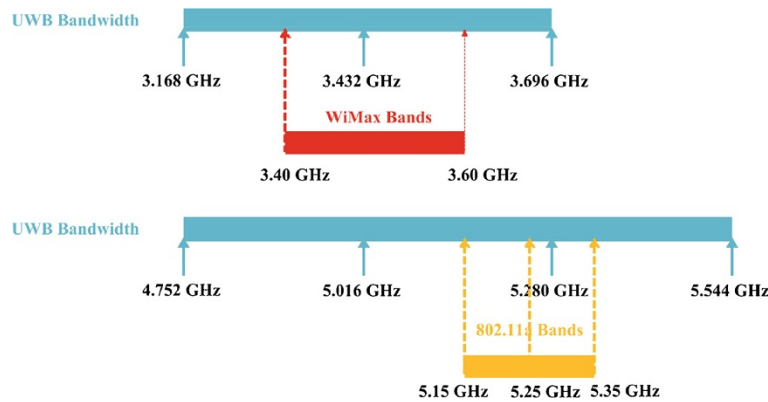
**Figure 1 Band overlapping between wireless systems.**

is dependent on the performance of the spectrum sensing algorithm [8].

In general cases, the characteristics of the PUs' signal are unknown to the CR-UWB. Thus, the non-coherent detection-based energy detection (ED) technique can be chosen to verify the availability of the overlapped spectrum [9]. In addition, ED's use of the Fourier transform (FT) function can be inherent from the OFDM-based UWB system [10]. According to the features of the ED [11], to determine the PUs' presence successfully, the length of the CR-UWB's spectrum sensing window shall be above a certain threshold which is roughly inversely proportional to the PUs signal's signal-to-noise ratio (SNR) received at the CR-UWB and dependent on the thresholds of the probability of false alarm (PFA) and probability of detection (PD).

For a CR-UWB system in which the duration of spectrum access is usually fixed [12], the length of the CR-UWB's spectrum sensing window determines the length of the transmission window. 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. Figure 3 shows a pattern of time resource allocation for the use of the available spectrum, i.e., the length fixed transmission opportunity (TXOP), in the CR-UWB system. Obviously, a high ratio between the transmission window length and the sensing window length is preferred [13]. Nevertheless, 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 and may result in an unacceptable spectral efficiency.

In this paper, we propose a spectrum sensing optimization algorithm in low-SNR regime, aiming at improving the spectral efficiency by finding the trade-off optimality of the spectrum sensing window length and the spectrum sensing performance. Followed by an optimized way of effective use of the available spectrum, the proposed
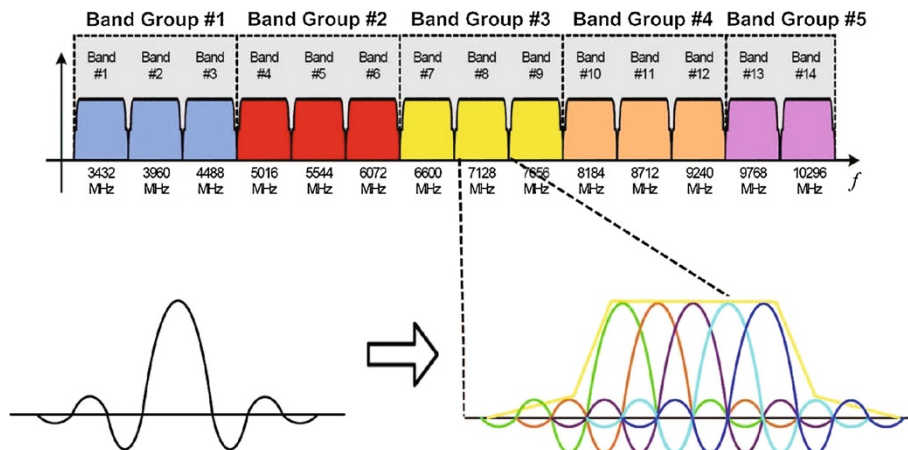
Figure 2 Band allocation of multiband OFDM-based UWB system.
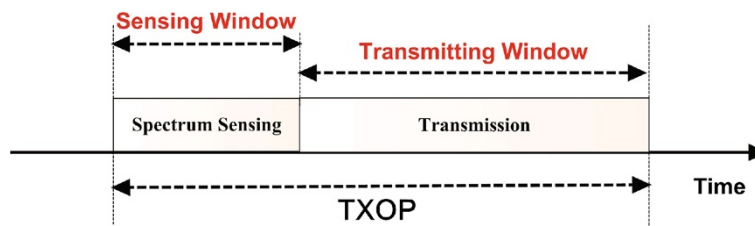
Figure 3 Time allocation in CR-UWB.

algorithm can maximize the proportion between the CR-UWB's transmission window length to the duration of the spectrum access while guaranteeing the PUs' operation.

The remainder of the paper is organized as follows. The 'Literature review' section gives a brief overview of the current spectrum sensing window optimization methods. The next section presents the spectrum sensing model and the formulation of the spectrum sensing window optimization problem. Then, the proposed sensing window optimization algorithm is demonstrated. Furthermore, the performance of the proposed algorithm is verified through numerical simulation which is in the section of numerical results. Finally, we give a conclusion to the paper in the final section.

Literature review

CR technology can be used in many areas [5,14,15]. Specifically, Stotas and Nallanathan and Peh et al. laid the fundamental work for dealing with the spectrum sensing window optimization problem in [16,17], respectively. The Lagrange dual optimization method was used by Stotas and Nallanathan in [16] 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 and Nallanathan's algorithm, the iterations required for identifying the multiple Lagrange multipliers' values are considerable. In [18], 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 [19]. However, the performance of Zou's algorithm in low PU SNR regime will be degraded considerably because the required sensing window length would be excessive.

System model

In the work, we assume that there exists a heterogenous network consisting of a single user CR-UWB network and a multiuser PU network, as shown in Figure 4. The single CR-UWB network contains one CR communication link, and the CR-UWB's infrastructure is in distributed

manner, i.e., *ad hoc* manner. The CR-UWB network overlaps with the PU network, in which the multiple PUs operate in the same band of the CR-UWB and within the range of being interfered by the CR-UWBs. We assume the use of the overlay spectrum sharing scheme [5], which indicates that the CR-UWB can access to the overlapped spectrum if and only if the CR-UWB's ED result shows that the PUs are temporarily absent. We also assume that an ideal notch filter is used in the CR-UWB system, hence the impact of the sideband interference can be ignored [20].

CR-UWB transceiver

Figure 5 depicts the architecture of CR-UWB transceiver. It shows that the spectrum sensing function is located in the cognitive engine block which lies posterior to the fast Fourier transform (FFT) engine of the CR-UWB's receiver side. The sensing results can be forwarded into the cognitive algorithm block for the CR-UWB system to dynamically use a radio resource allocation algorithm according to the sensing output.

Furthermore, for spectrum sensing in low-SNR regime, the low noise amplifier (LNA) and the automatic gain control (AGC) at the CR-UWB receiver side are enhanced compared with the conventional UWB transceiver [21]. Since the power of PUs' signals are much higher than that of the UWB user, which will lead to unlinear distortion in LNA, the original LNA is changed to an LNA whose dynamic range is wide enough to handle the power range of primary users' signals. Furthermore, due to the low transmit power of the CR-UWB, the AGC that is set for measuring the peer CR users' signals cannot detect the PUs signals. Hence, the AGC is adjusted according to the number of bits available in the analog-to-digital converter (ADC), so that the CR-UWB receiver can detect a wide variety of PUs power levels.

Spectrum sensing method

Our objective is to find the minimum value of the sensing window length in order to enhance the spectrum efficiency of the overlapped spectrum, in such a way that the time length for the effective data transmission
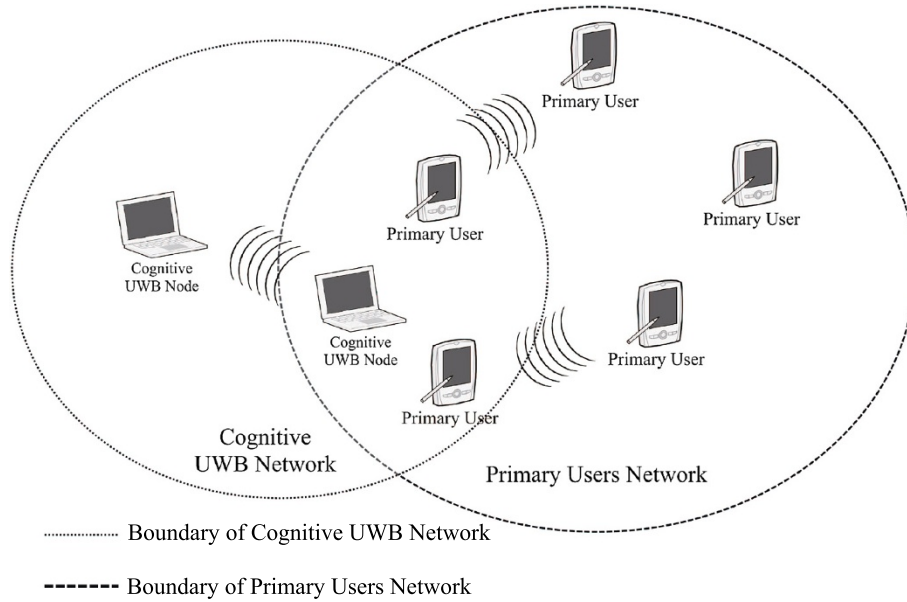
Figure 4 Illustration of a CR-UWB network with multiple PUs.

is maximized. Meanwhile, the value of the sensing window length needs to be large enough for the CR-UWB's ED to successfully determine the availability of the overlapped spectrum. An ED is implemented by averaging the squared magnitude of the K-point FFT of the received signal over the sensing period T which is proportional to the number of received signal samples. Given a fixed point FFT, the increase of the sensing period will improve the estimate of the signal energy [22]. The test statistic for an ED can be given by [23]

$$T(y) = \frac{1}{N} \sum_{n=1}^{N} |y(n)|^2, \tag{1}$$

where N denotes the number of received signal samples, and $y(n) = x(n) + u(n)$, $n \in [1, N]$, represents the discrete received signal at the CR user. Furthermore, $u(n)$ represents the noise and is a Gaussian independent and identically distributed (i.i.d.) random process with mean zero and variance $E[|u(n)|^2] = \sigma_u^2$. The PU's signal $x(n)$
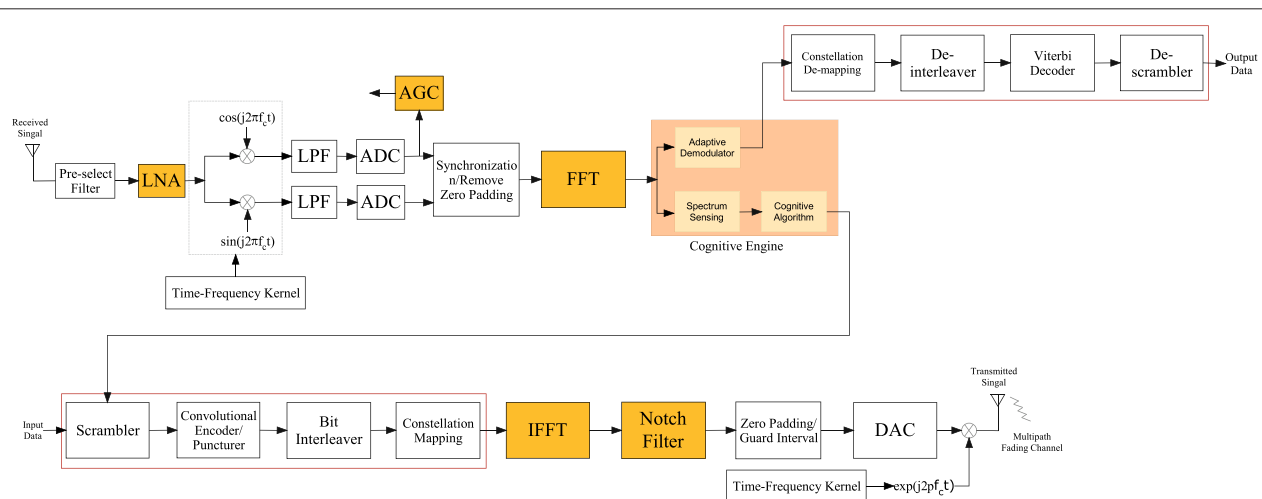
Figure 5 CR-UWB transceiver.

is an i.i.d. random process with mean zero and variance $E[|u(n)|^2] = \sigma_x^2$, and the parameter $\gamma_p = \sigma_x^2/\sigma_u^2$ denotes the received SNR of the PU.

The sensing result is determined by comparing $T(y)$ with the threshold, as

$$\begin{cases} \mathcal{H}_1, & T(y) > \epsilon(N) \\ \mathcal{H}_0, & T(y) < \epsilon(N), \end{cases} \tag{2}$$

where $\epsilon(N)$ represents the threshold, $\mathcal{H}_1$ denotes the hypothesis that the primary user is present, whereas $\mathcal{H}_0$ shows the hypothesis that the primary user is absent.

In an ED, the PD is the probability of detecting under the hypothesis $\mathcal{H}_1$ and is determined by the received signal's SNR, the threshold, and the number of signal samples [24]. Thus,

$$\begin{aligned} P_d &= P(T(y) > \epsilon(N)|\mathcal{H}_1) \\ &= P\left(\frac{T(y)/\sigma_u^2 - N - \gamma_p}{\sqrt{2(2\gamma_p + N)}} > \frac{\epsilon(N)/\sigma_u^2 - N - \gamma_p}{\sqrt{2(2\gamma_p + N)}}|\mathcal{H}_1 \right) \\ &\approx Q\left(\frac{\epsilon(N)/\sigma_u^2 - N - \gamma_p}{\sqrt{2(2\gamma_p + N)}} \right). \end{aligned} \tag{3}$$

For PF which denotes the probability of detecting that the licensed user under the hypothesis $\mathcal{H}_0$, the expression can be given as [24]

$$\begin{aligned} P_f &= P(T(y) > \epsilon(N)|\mathcal{H}_0) \\ &= P\left(\frac{T(y)/\sigma_u^2 - N}{\sqrt{2N}} > \frac{\epsilon(N)/\sigma_u^2 - N}{\sqrt{2N}}|\mathcal{H}_0 \right) \\ &\approx Q\left(\frac{\epsilon(N)/\sigma_u^2 - N}{\sqrt{2N}} \right). \end{aligned} \tag{4}$$

Hence, for a given target P_d and P_f, the minimum N is determined by manipulating Equations 3 and 4, as

$$N \approx \frac{2}{\gamma_p^2} \left[Q^{-1}(P_f) - Q^{-1}(P_d) \right]^2. \tag{5}$$

Note that the complexity of ED is proportional to $\mathcal{O}(\frac{1}{\gamma_p^2})$.

By observing Equation 5, $Q^{-1}(P_d)$ and $Q^{-1}(P_f)$ are expressed as

$$Q^{-1}(P_d) = \frac{\epsilon(N)/\sigma_u^2 - N - \gamma_p}{\sqrt{2(2\gamma_p + N)}}, \tag{6}$$

$$Q^{-1}(P_f) = \frac{\epsilon(N)/\sigma_u^2 - N}{\sqrt{2N}}. \tag{7}$$

Thus, P_d and P_f are related to each other by

$$P_d = Q\left(\frac{Q^{-1}(P_f)\sqrt{2N} - \gamma_p}{\sqrt{2(2\gamma_p + N)}} \right), \tag{8}$$

$$P_f = Q\left(\frac{Q^{-1}(P_d)\sqrt{2(2\gamma_p + N)} + \gamma_p}{\sqrt{2N}} \right). \tag{9}$$

Problem formulation

In the work, we model the spectrum sensing window optimization problem as a convex optimization problem. 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. Hence, the problem of optimizing the spectrum sensing window length is expressed as:

$$\mathbf{P1} \ \tau_s = \arg\max_{\tau_s} \ \beta S(1 - P_f)(1 - P(\mathcal{H}_1)) \tag{10}$$

subject to

$$P_f = Q\left(\frac{Q^{-1}(P_d)\sqrt{2(2\gamma_p + \tau_s f_s)} + \gamma_p}{\sqrt{2\tau_s f_s}} \right) \geq \bar{P}_f,$$

where S represents the spectral efficiency when the CR-UWB has full access to the overlapped spectrum where no PU is surrounded, β 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, as

$$\beta = \frac{(T_{\mathrm{op}} - \tau_s)}{T_{\mathrm{op}}}, \tag{11}$$

where T_{op} is the pre-defined length of the spectrum access window [12]. The constraint presents the threshold PAF of the CR-UWB's energy detector. The parameter τ_s represents the sensing window length which is determined by the PU's SNR, UWB's sampling frequency, and the target PFA; P_f and $\bar{P}_f$ represents the actual PFA and the target PFA, respectively, P_d represents the real-time PD, 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 [25]

$$P(\mathcal{H}_1) = p(x; \lambda t) = \frac{e^{-\lambda t}(\lambda t)^x}{x!}, \tag{12}$$

where x denotes the expected number of occurrences of PU's activations during the period of t which in our system model $t = T_{\mathrm{op}}$.

The objective function in Equation 10 shows that the spectrum efficiency of the overlapped spectrum is determined by multiplying S by the ratio of the CR-UWB's transmission window length to the total operating window length when the PU is not activated (i.e., $1 - P(\mathcal{H}_1)$), and the CR-UWB's energy detector successfully determines the absence of the PU within the overlapped spectrum (i.e., $1\text{-}P_f$).

For the constraints expressed in **P1**, γ_p represents the received PU signals SNR at the CR-UWB receiver, and f_s

denotes the UWB's sampling rate. Furthermore, $Q(x)$ is the one-dimensional Gaussian Q-function, as [26]

$$Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{y^2}{2}\right) dy, \qquad (13)$$

For a certain threshold $\bar{P}_f$, the corresponding threshold sensing window length $\bar{tau}_s$ can be determined by manipulating Equation 5, as

$$\tau_s \geq \frac{2}{\gamma_p^2 f_s}(Q^{-1}(\bar{P}_f) - Q^{-1}(\bar{P}_d))^2, \qquad (14)$$

where $\bar{P}_d$ denotes the target PD which can be calculated through the use of the receiver operating characteristic (ROC) curves [11], and it shows that the value of the CR-UWB's spectrum sensing window length should not be less than the threshold in order to ensure a successful detection of the availability of the overlapped spectrum. The threshold is determined by the value of $\bar{P}_f$, $\bar{P}_d$, the received PU signals SNR γ_p, and the CR-UWB system's sampling rate f_s.

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

$$\textbf{P2} \ \tau_s = \arg\max_{\tau_s} \ \beta \left[1 - Q\left(\frac{Q^{-1}(P_d)\sqrt{2(2\gamma_p + N)} + \gamma_p}{\sqrt{2N}} \right) \right], \qquad (15)$$

subject to

$$P_f = Q\left(\frac{Q^{-1}(P_d)\sqrt{2(2\gamma_p + \tau_s f_s)} + \gamma_p}{\sqrt{2\tau_s f_s}} \right) \geq \bar{P}_f,$$

where $N = \tau_s f_s$ represents the number of spectrum sensing samples of CR-UWB's energy detector,

Figure 6 shows the time for spectrum sensing deduces exponentially when the received SNR γ_p increases. At low γ_p (<15dB), the sensing time length is longer when the target value of P_f is reduced. For example, for the target $P_f = 0.10$, $P_d = 0.90$, and $P_f = 0.01$, $P_d = 0.99$, the time for spectrum sensing τ_s is 250 and 820 μs (1μs = 10^{-6}s), respectively. When the value of γ_p increases to a higher level, such as over 12 dB, the sensing time difference between the two target values of P_f becomes minor.

In Figure 7, it shows that the value of α increases exponentially with the increase of the received SNR γ_p. When γ_p is low (< −17.6 dB) for $P_f = 0.01$, $P_d = 0.99$, over 50% of the transmission opportunity is used for spectrum sensing. Thus, the cognitive UWB system can reach a higher spectrum efficiency if the UWB system totally use the TXOP for transmission on the non-overlapped spectrum (i.e., the remaining 64 subcarriers) than performing the spectrum sensing first in order to use the 128 subcarriers for transmission. When the value of γ_p continues to
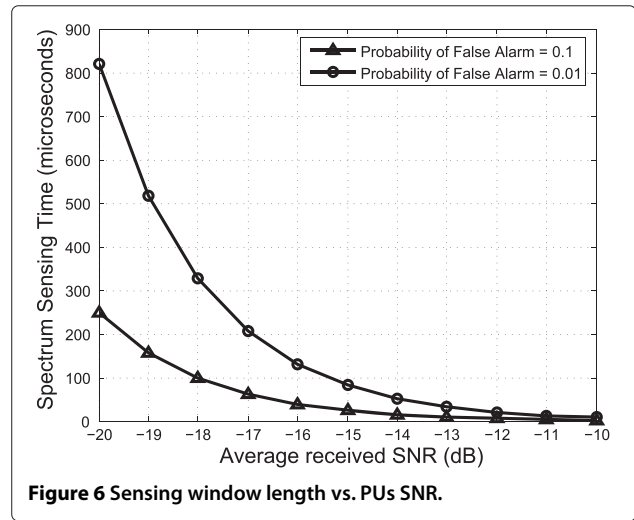
Figure 6 Sensing window length vs. PUs SNR.

increase, the fraction of time differences for UWB's data transmission under the two target values of P_f becomes minor.

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 trade-off 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 microseconds, as shown in Figure 8.

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
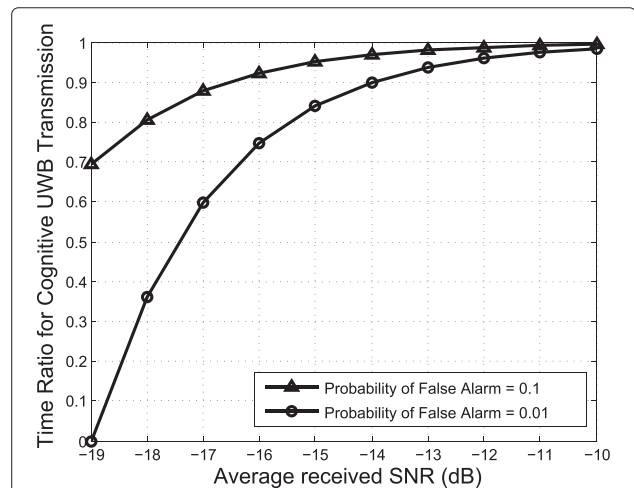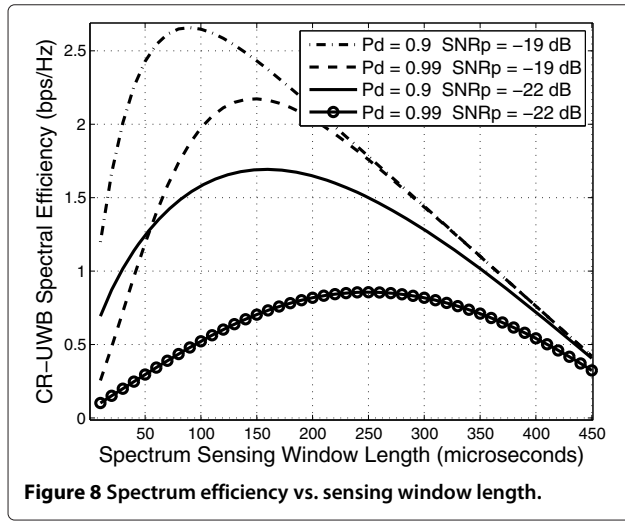
Figure 7 Transmission window length ratio vs. PUs SNR.

Figure 8 Spectrum efficiency vs. sensing window length.

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 8 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

$$f_r(\tau_s) = -\frac{1}{T_{\text{txop}}} - \left[Q'(\tau_s) - \frac{1}{T}(Q(f(\tau_s)) + Q'(f(\tau_s))) \right] = 0, \tag{16}$$

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

$$f(\tau_s) = \frac{Q^{-1}(P_d)\sqrt{2(2\gamma_p + \tau_s f_s)} + \gamma_p}{\sqrt{2\tau_s f_s}} \tag{17}$$

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

$$f'(\tau_s) = \frac{Q^{-1}(P_d)f_s}{2\sqrt{(2\gamma_p + \tau_s f_s)\tau_s f_s}} - \frac{\sqrt{2}f_s(Q^{-1}(P_d)\sqrt{(4\gamma_p + 2\tau_s f_s)} + \gamma_p)}{4(\tau_s f_s)^{3/2}} \tag{18}$$

Nevertheless, computing the optimal τ_s in closed form is complex. Hence, line search method is used to approximately find the optimal spectrum sensing window length. Figure 9 illustrates the flow diagram of the sensing time optimization algorithm. By initiating the values of $\bar{P}_f$, f_s and T_{op}, the target value of $\bar{P}_d$ can be identified, which in turn can determine the required $\bar{\tau}_s$ that is needed for

Figure 9 Flow diagram of sensing window length optimization.

Figure 10 Spectral efficiency vs. SNR$_p$.
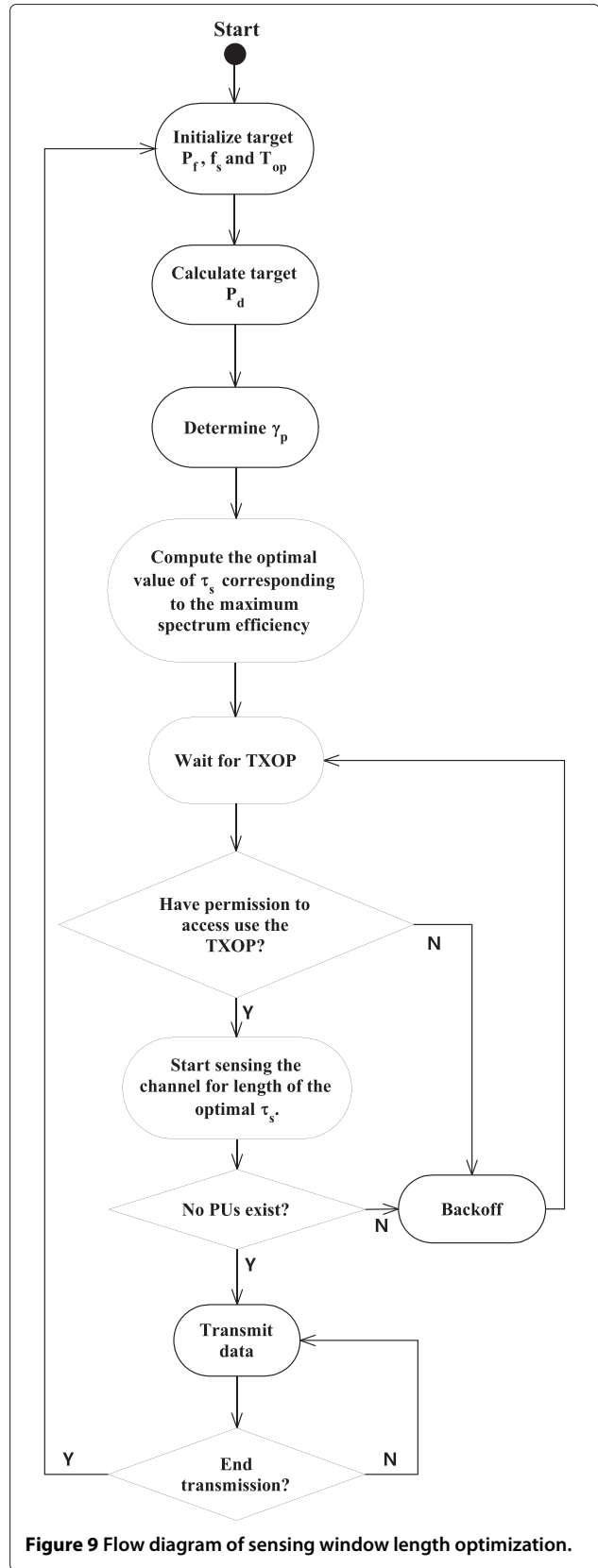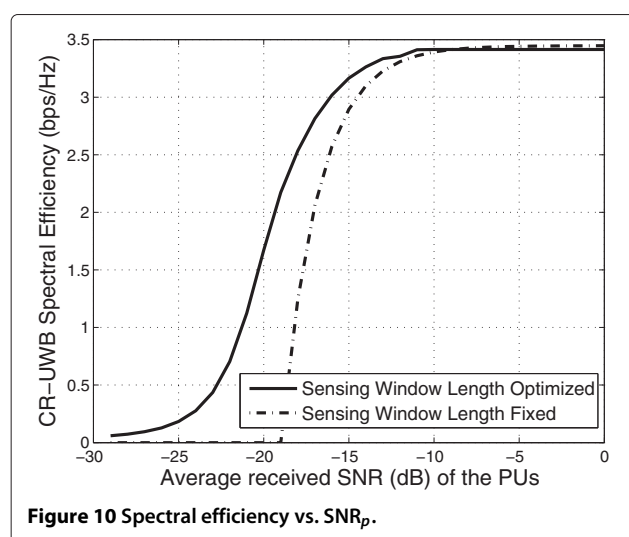
successfully detecting the availability of the specific spectrum, under a certain detected value of γ_p. Using line search method, the optimal window length value of τ_s can be found, which can maximize the spectrum efficiency while guaranteeing the operation of the PUs. Then, by successfully accessing the wireless medium through the use of the Carrier sense multiple access with collision avoidance (CSMA/CA)-based MAC scheme [12], the CR-UWB station starts using sensing the spectrum using the optimal τ_s. Finally, the sensing results are used by the CR-UWB's transmission function which is shown in Figure 5, to dynamically allocate the radio resource for data transmission, until the transmission period is over.

Numerical simulation
To validate our algorithm performance in terms of spectral efficiency enhancement, we combine the proposed sensing window length optimization algorithm with the water-filling based transmission scheme proposed in [7]. 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 a water filling-based algorithm [7] 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 PF is set to 0.01.

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 Figure 10. 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 $\bar{P}_d$.

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 ED-based CR-UWB system to find the optimal trade-off 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.

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