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UWB Cognitive Radios

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1. Introduction

In this chapter we present UWB communication as a potential candidate for cognitive radio technology. Cognitive radios are intelligent radios that could adopt itself by sensing and learning the radio environment and optimize its transmission strategies to maximize the utilization of the scarce radio resources such as the radio spectrum. This has been motivated by the radio regulatory bodies around the world (EC, 2007; FCC, 2003) to utilize unused radio spectrum known as white space in the spatio-temporal domain. In the recent years UWB communication has emerged as a potential candidate for the CR technology due to its ability to share the spectrum with others for short range wireless communications. In this context we present the concept of cognitive radios and the necessary techniques to adopt UWB as cognitive radios in this chapter. Especially, we enhance on the fundamentals of cognitive radios and spectrum sensing which enable the UWB radio to learn the radio environment. We also touch upon other cognitive radio related topics that are related to UWB communications such as dynamic spectrum access, interference mitigation and localization techniques. Furthermore, we present some potential applications for the use of UWB based cognitive radios which are derived from the European Union funded projects EUWB (EUWB, 2008) which is one of the biggest UWB projects that the world has seen so far, and the C2POWER project (C2POWER, 2010) which is related to energy efficiency in short range wireless communications with the use of cognitive radios. In this chapter we do not consider the technological aspects related to the use of cognitive radios for energy efficiency but only consider the use of cognitive radios for dynamic spectrum access. However, at the end of the chapter we present a scenario for the use of cognitive radios for energy efficiency derived from (C2POWER, 2010).

In the material presented in this chapter we mainly consider the high data rate UWB radios based on the Multi-Band Orthogonal Frequency Division Multiplexing (MB-OFDM) technique following the Wimedia specifications (Wimedia-PHY, 2009). The OFDM based transceiver design makes it feasible for the UWB radio to sense the radio environment and dynamically change the transmission parameters accordingly. This makes the UWB radios much more attractive and to suit cognitive radio technology that require having intelligence and adoptability in the radio itself. Moreover, the low transmit power in UWB communications also makes it feasible to have secondary user access to the spectrum without interfering with the primary users of the spectrum. The concepts of secondary users and primary users are treated subsequently in this chapter.

2. Cognitive radio fundamentals

The term cognitive radio was coined by Joseph Mitola (Mitola, J. & Maguire Jr. G.) considering ideal context aware radios with embedded intelligence. Mitola's vision of cognitive radios spans across all the layers of the communication protocol stack emphasizing on the need for optimum utilization of the radio resources by adopting its transmission policies and strategies. The adaptation of the local policies is based on sensing and learning the environment or by being informed about the radio environment by an information broker in the network. Haykin (Haykin, S. 2005) then adopted Mitola's ideal cognitive radio concept to wireless communications by defining the corresponding communications and signal processing problems associated with cognitive radios in the lower layers of the protocol stack. Here we present the fundamentals of cognitive radios explaining the cognitive engine and the cognitive cycle as described by Mitola and Haykin. We present the concept of white-space in the spatio-temporal domain in regards to spectrum utilization and the underlay and overlay technologies for dynamic spectrum access.

2.1 Spectrum classification in a broader sense

First let us classify the spectral usage in the spatio-temporal domain. By computing the power spectra of the received radio stimuli at a particular point and time one could broadly classify the spectra into three types (Haykin, S. 2005), as given below.
Black Spaces: spectra occupied by high-power 'local' interferers.
Gray Spaces: spectra occupied partially by low power interferers.
White spaces : spectra free of radio frequency interferers except for ambient natural and man-made noise.

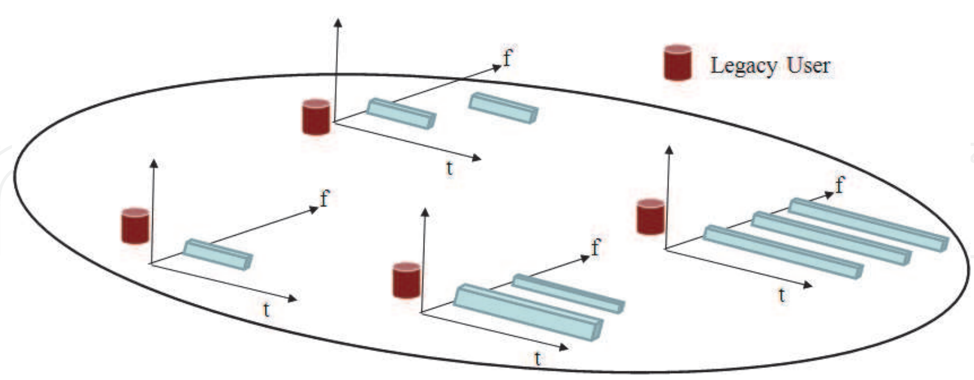

Fig. 1. The evolution of 'spectrum holes' in the spatio-temporal domain

One could clearly see that the above classification is a function in the spatio-temporal domain. For example, 'black', 'gray' and 'white' spaces could appear and disappear back and forth at a particular location over time. Therefore it is necessary to sense and learn the radio environment in order to maximize the spectral usage opportunistically. In other words detecting ’spectrum holes’ as it is termed is quite crucial for dynamic spectrum access. Figure-1 depicts the concept of ’spectrum hole’ evolution in the spatio-temporal domain.

2.2 Spectrum sharing in cognitive radio networks: ’Underlay’ and ’Overlay’ techniques

With cognitive radio technology the concept of ’primary users’ and ’secondary users’ of the spectrum are developed. The primary users are the incumbent users with the exclusive rights to use the spectrum at anytime and the secondary users, also known as the cognitive radio users, are the users that use the spectrum without interfering with the primary users. There are basically two spectrum sharing techniques considered for cognitive radio networks for maximizing the spectral efficiency between the primary and the secondary users. First is the ’spectrum underlay’ technique and second is the ’spectrum overlay’ technique.

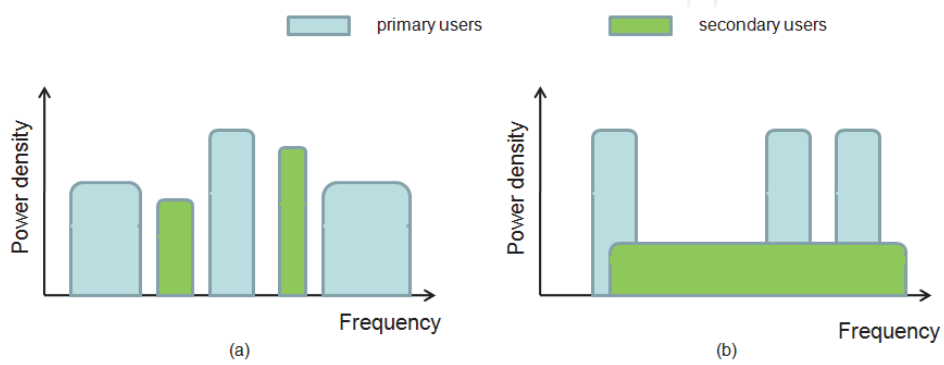

Fig. 2. Spectrum sharing in cognitive radio networks, with (a) overlay and (b) underlay sharing techniques.

In the ’spectrum underlay’ method the secondary users can utilize the spectrum simultaneously with the primary users without exceeding a predefined interference level to the primary users. Secondary users in this case can share the spectrum such that the total interference power from the secondary users to the primary users are controlled below the interference limit set by the relevant regulatory authorities. The characterization of such interference limit is given in the next subsection. Figure-2 depicts the concept of spectrum underlay technology. UWB radio technology due to the low powered transmissions in the ultra wide band frequency range is therefore a potential candidate for deploying spectrum underlay technology for spectral sharing. Using the low powered transmissions and making sure that the interference limit is not exceeded UWB radios can potentially share the spectrum with the primary users and coexist.

In the ’spectrum overlay’ method the cognitive radios can identify the spectrum holes in the spatio-temporal domain and opportunistically utilize them by giving higher priority to the primary users. Whenever a primary user is not using the spectrum secondary users (cognitive radios) are allowed to transmit however when a primary user is detected in that particular band then secondary users need to immediately vacate the band by stopping transmitting in that particular band. In this sense spectrum sensing and primary user detection become a crucial functionality for reliably detecting the primary users in the environment in the spatio-temporal domain. Figure-2 depicts the concept of spectrum overlay technology at a particular time in some space. The MB-OFDM based UWB technology is considered as a potential candidate for spectrum overlay technology for spectrum sharing by inherently making use of the OFDM transmission technique. By using OFDM, UWB devices can dynamically turn on and off the corresponding subcarriers depending on whether any primary users exist or not in a particular band in the environment. In other words the transmission spectrum of UWB radios can be sculpt according to the presence of the primary users in the respective frequency bands in the environment.

2.3 The interference temperature limit

The interference temperature T_I is a measure of the interference power level due to wireless transmissions at a particular location as defined by the FCC in (FCC, 2002). The interference temperature follows a similar definition as to the thermal noise temperature in receivers. It is well known that the thermal noise power P_n in receivers is given by (Sklar, B.),

$$P_n = kT_N B \tag{1}$$

where $k = 1.38 \times 10^{-23}$ is the Boltzmann's constant, B (Hz) is the receiver operating frequency bandwidth and T_N (in degrees Kelvin unit) is the noise temperature. Likewise the total interference power P_I due to the transmissions of wireless devices and natural interferences at a particular point in space can be characterized by,

$$P_I = kT_I B \tag{2}$$

The interference temperature limit $T_I^{\max}$ therefore is an upper limit on the value of T_I that can be used to control and limit the interference in the radio environment. Such limits for the interference temperature can be used to enable the underlay spectrum sharing technique by coordinating or policing the interference level in the environment generated by the secondary users to the primary users.

2.4 The cognitive cycle

The cognitive cycle is the term describing the activities involving the intelligence of the radio device such as sensing, learning and adopting. In (Mitola, J. & Maguire Jr. G.), Mitola had presented a generic cognitive cycle that corresponds to his view of ideal cognitive radios. By adopting this model, Haykin then presented a similar cognitive cycle model in (Haykin, S. 2005) by mainly describing the PHY and MAC layer aspects of the radio device considering the communications and signal processing functionalities. Here we explain both the cognitive cycles described by Mitola and Haykin.

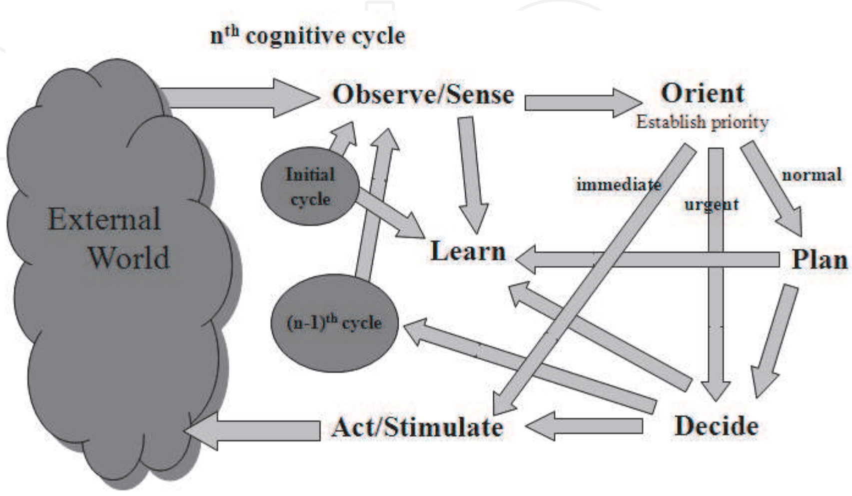

Fig. 3. Cognitive Cycle described by (Mitola, J. & Maguire Jr. G.)

Figure-3 depicts the cognitive cycle described by Mitola. In the figure the radio observes and senses the external world and orients itself according to the internal policies and plans before making a decision on how to act upon that situation. Once the decision is made the radio then acts accordingly. Then in the next and the consecutive cycles it goes through a similar process until it decides not to operate. The cognitive radio learns from the observations as shown in the figure. The core of the cognitive cycle that lies inside the radio is known as the cognitive engine.

The equivalent cognitive cycle presented by Haykin is depicted in Figure-4. In this figure, the corresponding signal processing and communications functionalities associated with the radio is presented within the cognitive engine. As shown in the figure, the cognitive radio observes the radio environment using the sensed radio stimuli and creates a radio environment map of the potential radios in the environment considering the spatio-temporal usage of the frequency bands. This information is then used together with the channel state estimation by the transmitter to adopt its transmissions accordingly.

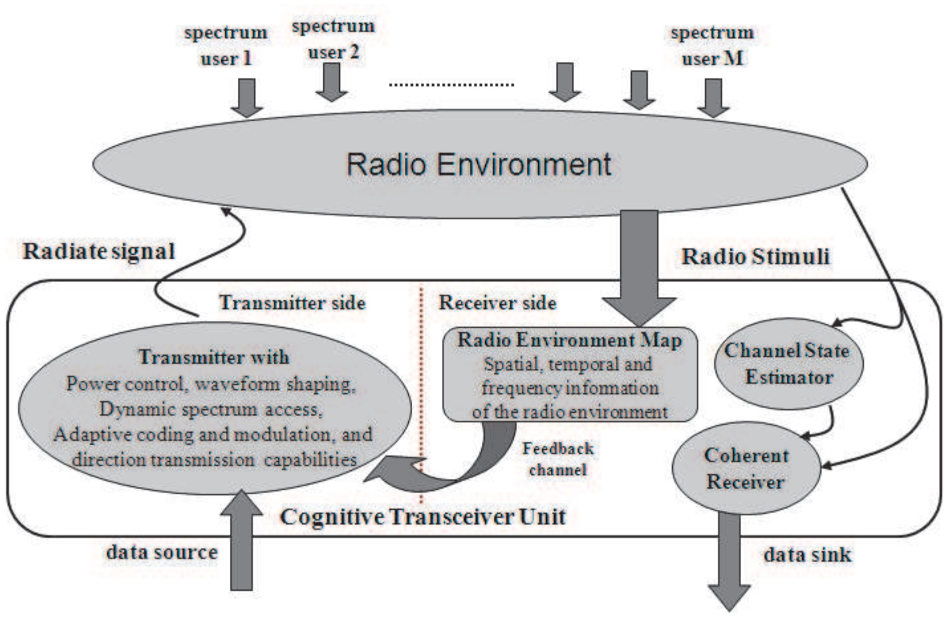

Fig. 4. Cognitive Cycle corresponding to the communications and signal processing aspects in the radio, as described by (Haykin, S. 2005)

The cognitive engines presented in Figure-3 and Figure-4 are only the conceptual ones which include the basic functionalities required for the radio to have intelligence. The spectrum sensing functionality helps the radio to observe the radio environment, and is one of the hot topics in the field of cognitive radios. Spectrum sensing is covered later in Section-5. The radio environment map is then created with the use of spectrum sensing information and the radio-localization functionality (if available) of the cognitive radio. Localizing a radio in the environment is not always feasible given the fact that the localization task needs to be performed blindly. Once the cognitive radio nodes have a good understanding of the radio environment it would then perform power control with appropriate interference mitigation techniques in the spatio-temporal domain to transmit its data. Furthermore, other functionalities also can be added into the cognitive engine depending on the applications and any specific requirements appropriately.

3. Dynamic spectrum access

The radio spectrum can be utilized by considering various access strategies, methodologies or policies. In this section we provide a quick background on the spectrum access models to explain how cognitive radios are used for dynamic spectrum access. Spectrum access models can be classified as command and control model, exclusive-use model, commons model and the shared model (Hossain, E. et. al.). In the shared use model the secondary user of the spectrum will opportunistically access the spectrum without interfering with the primary user of the spectrum, in the exclusive use model the unlicensed secondary user can be granted access to the spectrum by the licensed primary user, and in the commons model the secondary user can access the spectrum without any restrictions. In Figure-5 we present a taxonomy of the different spectrum access models.

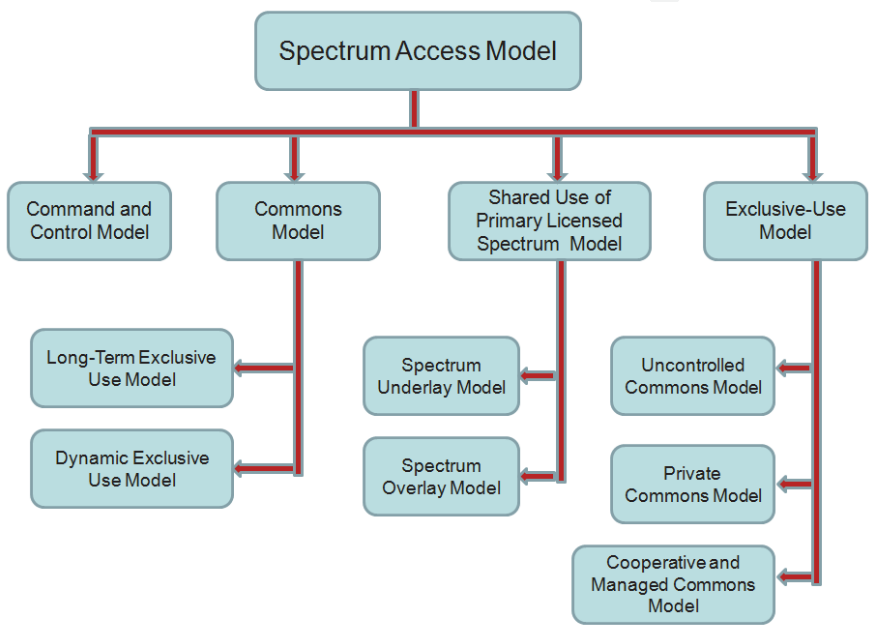

Fig. 5. Classification of spectrum access models

For a detailed description of the different access models the reader is referred to (Hossain, E. et. al.). In the previous section we briefly described the access model that is of interest to us which is the shared spectrum access model that includes the spectrum underlay and overlay techniques. In the 'shared' model the concept of primary and secondary users of the spectrum are derived and the spectrum can be shared simultaneously between the primary and the secondary users of spectrum. The primary users are the incumbent users of the spectrum however the secondary radios also can use the spectrum. In this case the secondary radios need to make sure that they do not interfere with the primary radio transmissions, and as long as the interference constraint is met the secondary users can use the spectrum transparently to a primary user.

4. UWB as cognitive radio, and coexistence

As described previously cognitive radio nodes require intelligence and self adoptability in order to dynamically adopt its strategies based on the time varying radio environment. In this section we see how UWB devices can suit such requirements and be considered as a potential candidate for cognitive radio technology. Based on MB-OFDM transmission, Figure-6 depicts how UWB radios could be used as secondary radios based on cognitive radio technology for sharing the spectrum with the other users. In this section we further describe how the UWB radios can be considered to adopt both underlay and overlay spectrum sharing models.

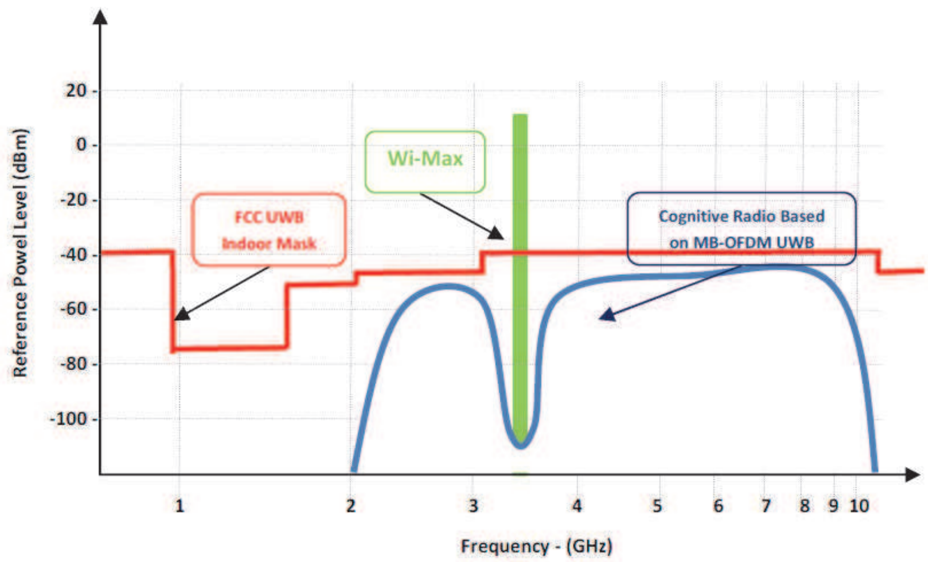

Fig. 6. Intelligent spectrum sharing mechanism based on underlay and overlay policies by UWB radios using cognitive radio technology

As we know there exist many radio technologies in the UWB frequency range operating in the licensed as well as the unlicensed frequency bands. The UWB radios therefore need to coexist with all the radios in the frequency range which makes UWB as a potential candidate for cognitive radio technology which maximizes the usage of the scarce spectrum. In this section we further consider the coexistence of various spectrum users in the UWB frequency range with the MB-OFDM based UWB radios. In particularly, we discuss the policies and requirements for the UWB radios to coexist with the other radios and utilize the spectrum as a secondary user considering both underlay and overlay spectrum access methods. Power controlling with the concept of interference temperature limit, spectrum sculpting together with detect-and-avoid (DAA) techniques are some of the strategies used by UWB radios in order share the spectrum with the primary users. Below we provide some background on spectrum sculpting and power control in UWB radios in the context of spectrum sharing, and later we present detect-and-avoid technique in detail.

4.1 Spectrum sculpting

For the UWB radios to share the spectrum with the primary users using the overlay method it needs to shape its transmission spectrum in such away that the primary users are not interfered. Spectrum sculpting techniques are used for shaping the spectrum in UWB radios (Wang, Z.; Yamaguchi, H.). The two most common spectrum sculpting methods are the spectrum shaping in time domain using shaped pulses and spectrum shaping in the frequency domain using tone nulling (in OFDM systems). The time domain method in general may not be possible to shape the spectrum in all the cases, the frequency domain tone nulling method on the hand can provide better performances in terms of shaping the spectrum. The tone nulling technique can cause spectral overshoots in the transmission band and hence various derivatives of this method are also considered such as enhanced active interference cancelation as proposed in (Wang, Z.). The example shown in Figure-6 clearly depicts how the spectrum sculpting technique is used in UWB radios in order to coexist and share the radio spectrum with the primary user radios in the environment.

4.2 Power control

Power control in wireless and mobile communications is a well studied topic for more than twenty years. It has attained more attention in the recent years for potential spectrum sharing in cognitive radio networks. Traditionally power control was considered for maximizing the transmission rate with fare-scheduling without degrading the QoS of the other users in the environment. In a similar context power control is also considered for cognitive radio networks as presented in (Gu, H.; Radunovic, B.; Xing, Y.; Zhang, L.). Here we briefly explain the concept on power control for dynamic spectrum sharing with underlay technology in cognitive radio networks by having the total interference power as a constraint.

Suppose P_I is the interference power limit corresponding to the interference temperature T_I as explained in (2). If there exist K number of cognitive radios in the environment sharing the spectrum with the incumbent users, then the total interference caused to the l^{th} primary user is given by,

$$I_l = \sum_{k=1}^{K} h_{kl} P_k \tag{3}$$

where, P_k is the transmitted power from the k^{th} cognitive radio node, and h_{kl} is the channel gain from the k^{th} cognitive radio node to the l^{th} primary user in the environment. In order to comply with the interference regulatory level, for the interference caused from the secondary users to the primary users, the following constraint should be met,

$$I_l = \sum_{k=1}^{K} h_{kl} P_k \leq P_I \forall l \tag{4}$$

The cognitive radio nodes on the other hand would like to achieve the highest possible transmission rate which is related to the received signal to interference ratio γ_{km} at the m^{th} secondary receiver where $m = 1 \ldots K$ and $m \neq k$, given by,

$$\gamma_{km} = \frac{h_{km} P_k}{\sum_{u=1, u \neq k, m}^{K} h_{um} P_u + \sigma_m^2} \tag{5}$$

where, h_{km} is the channel gain from the transmitter k to the intended receiver m, h_{um} is the channel gain from the transmitter u to the unintended receiver m, P_u is transmitted power from the transmitter u, and σ_m^2 is the receiver noise power at the receiver node m. Then in order for the secondary communication pair $\{k, m\}$ to have the best possible transmission rate, considering the constraint in (4), the simplest optimization strategy for power control is given by,

$$\hat{P}_k = \max_{P_k} \gamma_{km}, \text{ such that } I_l \leq P_I \tag{6}$$

It might be difficult to measure the interference power at the primary user node unless the primary user cooperates. In such situations there can be a power controller or a monitor serving the purpose of controlling the power by measuring the total interference power at some central location. In literature one could find various cooperative and distributed power controlling methods using game theoretic approaches which we do not cover in this chapter.

5. Spectrum sensing

Spectrum sensing is one of the crucial functionalities of a cognitive radio in order to learn the radio environment. Various spectrum sensing techniques exist (Kandeepan, S. et. al; Yucek, T. and Arslan,H.) and in general could be classified as 1) energy based sensing, 2) cyclostationary feature based sensing and 3) matched filter based sensing. The energy based sensing is the simplest method to sense the environment in a blind manner, the cyclostationary based sensing may require some information about the spectral-user signal characteristics, and the matched filter based sensing requires the complete information of the spectral-user signal. In this section we elaborate in detail on the various spectrum sensing techniques and their related detection performance for MB-OFDM based sensing. Moreover, we present collaborative sensing techniques in order to address the 'hidden node problem'.

Let us provide some background on spectrum sensing prior to presenting the related techniques. Spectrum sensing and detecting the presence of a radio in the environment is treated as a classical statistical detection problem (Kay, S.). We define the two binary hypotheses H_0 and H_1 to indicate the absence and the presence of the primary users in the environment respectively. In the discrete signal domain this could be represented as,

$$r(n) = \begin{cases} \nu(n), & H_0 \\ s(n) + \nu(n), & H_1 \end{cases} \tag{7}$$

where $\nu(n)$ is the additive Gaussian channel noise and $s(n)$ is the received signal. If the test statistic that is used for the detection is given by $\xi(r(n))$, which is a function of the sensed signal $r(n)$ with $n = 1, 2 \ldots N$, then the detection criteria is given by,

$$d = \begin{cases} 0; \ \xi < \lambda \\ 1; \ \xi \geq \lambda \end{cases} \tag{8}$$

where, λ is known as the detection threshold. The probability of detection and the probability of false alarm are then defined as,

$$P_D = Pr[d = 1 | H_1] \tag{9}$$

$$P_{FA} = Pr[d = 1 | H_0] \tag{10}$$

The probability of miss detection on the other hand is defined by $Pr[d = 0 | H_1]$, and thus is given by $P_M = 1 - P_D$. In general the detection threshold λ is chosen in order to trade off between the detection and false alarm probabilities. Different criteria can be used in order to find the optimal threshold which is a well treated topic in the literature of statistical detection, which we do not present in this chapter. In the subsequent sections we provide various ways to derive the test statistic ξ used for the detection of primary users.

5.1 The hidden terminal problem

Prior to presenting the spectrum sensing techniques we present why spectrum sensing is treated as an important topic in cognitive radio literature. We mentioned that the detection performance is characterized by the probability of successfully detecting the radio and the probability of false alarm. In cognitive network applications the regulatory bodies are quite strict on secondary nodes causing any interference to the primary users, in this sense the primary users need to be reliably detected by the secondary users with a high detection probability (close to 100% or $P_D \simeq 1$). The detection probability usually depends on the signal to noise ratio of the received signal, the received signal power depends on how far the transmitting node is from the sensing node characterized by the path loss. Moreover, channel fading is also a factor that affects the received signal power. In this sense, radio nodes (primary users) closer to the cognitive radios are easily detected with a higher probability of detection compared to the radio nodes that are further away from the cognitive radios. When the primary user radios are not detected by the cognitive radio nodes they do not appear in the radio environment map created by the cognitive radio nodes, and hence the primary user nodes become hidden to the cognitive radio nodes. This is known as the 'hidden terminal problem'. Figure-7 depicts a typical hidden terminal problem scenario. In the figure, CR-1 is unable to detect the PU and hence the PU node is hidden from the CR-1 node. The hidden node problem can create interference from the secondary nodes to the primary nodes and hence therefore harming the communication rights of the primary radios in the allocated band and violating the regulatory requirements. The hidden terminal problem also can harm the performance of secondary user communications interfered by the primary user in this case. Therefore, various spectrum sensing and detection techniques are considered to solve the hidden terminal problem to increase the detection probability for detecting the primary users in the environment.

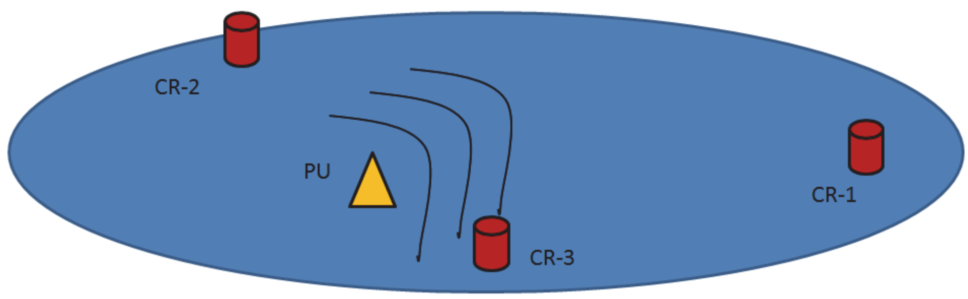

Fig. 7. An example of the hidden terminal problem, where the PU node is hidden from CR-1.

5.2 Spectrum sensing with energy detection

The energy detector is the simplest spectrum sensing method for detecting primary users in the environment in a blind manner (Urkowitz, H.). It is computationally efficient and also be used conveniently with analog and digital signals (or in other words at the RF/IF stages or at the base band). It also has a well known drawback in the detection performance when the noise variance is unknown to the sensing node. When the signal to noise ratio is very low the knowledge of the noise power can be used to improve the detection performance of the energy detectors. In energy detectors, the energy of the received signal is computed over a time period T or equivalently over N samples in the discrete domain and used as the test statistic, where $T = NT_s$ and T_s is the signal sampling period. The test statistic at the base band considering the complex envelope of the received signal is therefore given by,

$$\xi = \int_{t_1}^{t_2} r(t)\tilde{r}(t)dt \tag{11}$$

where, $\tilde{r}(t)$ is the complex conjugate of $r(t)$. The signal to noise ratio (SNR) is then defined based on the received signal $s(t)$ for $t_1 < t \leq t_2$ for some $t_1, t_2 \in \mathbb{R}^+$, given by,

$$\rho = \frac{1}{\sigma_i^2[t_2 - t_1]} \int_{t_1}^{t_2} s(t)\tilde{s}(t)dt \tag{12}$$

Note that based on the transmission pattern of the primary user the instantaneous signal to noise ratio would vary, here however we assume ρ to be a constant. For the discrete signal on the other hand, the energy based test statistic is given by,

$$\xi \approx T_s \sum_{n=0}^{N-1} r[n]\tilde{r}[n] \tag{13}$$

where, N is the total number of complex samples and is also known as the time-bandwidth product (Urkowitz, H.). Note that in (12) there are essentially N number of real component samples and N number of imaginary component samples. Considering the discrete domain test statistic the detection criteria is then given by,

$$d = \begin{cases} 0; \ \xi < \lambda \\ 1; \ \xi \geq \lambda \end{cases} \tag{14}$$

In order to compute the detection probability and the false alarm probability we consider the distribution of the test statistic ξ. The energy based test statistic ξ follows a non-central and a central chi-sqaure distribution under H_0 and H_1 respectively with $2N$ degrees of freedom. Using the distributions of the test statistic under H_0 and H_1 we can derive the detection probability and the false alarm probability using equation (9) and (10) and in closed form expressions as (Dingham, F.,F.),

$$P_D = Q_N(\sqrt{2N\rho}, \sqrt{\lambda}) \tag{15}$$

$$P_{FA} = \Gamma(N, \lambda/2) \tag{16}$$

where, $\Gamma(a,b) = \frac{1}{\Gamma(N)} \int_b^\infty u^{a-1} \exp(-u) du$ is the regularized upper incomplete Gamma function, $\Gamma(.)$ is the Gamma function, $Q_N(a,b) = \int_b^\infty u^N \exp(-(u^2+a^2)/2) I_{N-1}(au)/a^{N-1} du$ is the generalized Marcum Q-function, and $I_{N-1}(.)$ is the modified Bessel function of first kind with order $N-1$.

Let us look at some results for the detection performance of the energy detector in the additive Gaussian noise channel by plotting the complementary receiver operating characteristics (C-ROC) curve. The C-ROC depicts the probability of false alarm in the x-axis and probability of miss detection in the y-axis. Figure-8 shows the C-ROC curves for the energy detector for various values of signal to noise ratio levels ρ. As we observe from the figure, the detection performance improves with increasing values of ρ by achieving lower miss detection probabilities for lower false alarm probabilities when ρ increases. Figure-9 on the other hand shows the C-ROC curves for various values of N, and again we observe that the detection performance improves with increasing values of N.

Note that the analytical results presented here do not consider the wireless channel effects such as fading or shadowing, authors in (Dingham, F.,F.) and (Atapattu. S., et. al.) have presented closed form expressions for the detection probability for the energy detector considering various wireless channels which we do not cover in this chapter.

5.3 Spectrum sensing with cyclostationary feature detection

The cyclostationary feature analysis is a well developed topic in the literature of signal processing (Gardner, W.). In wireless communications, depending on the modulation type, data rate and carrier frequency etc. the transmitted signals show very strong cyclostationary features, especially when excess bandwidth is utilized. Therefore identifying the unique set

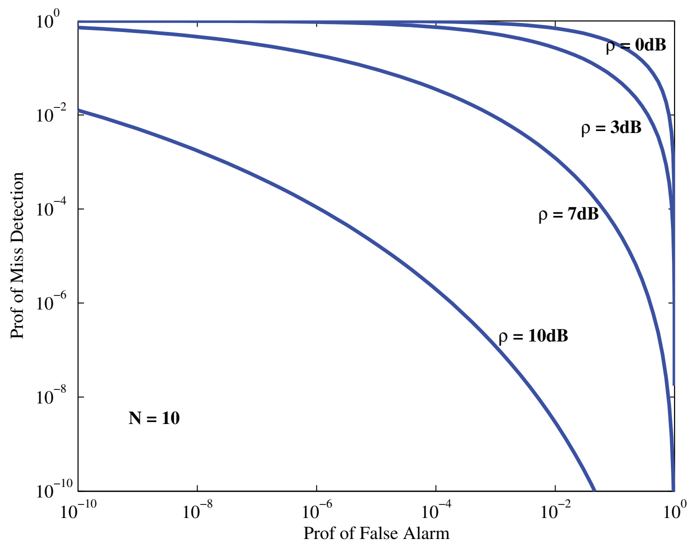

Fig. 8. Complementary ROC curves for the energy detector for various signal to noise ratio levels.

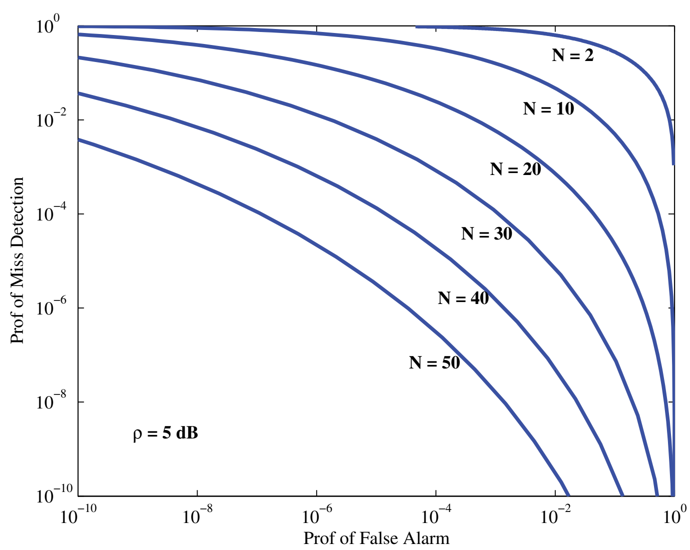

Fig. 9. Complementary ROC curves for the energy detector for various values of time-bandwidth product N.

of features of a particular radio signal for a given wireless access system can be used to detect the system based on its cyclostationary features. In the context of spectrum sensing some studies have been performed in using the cyclostationary features to detect the primary users in the environment (Kandeepan, S.; Kyouwoong, K.). For sufficient number of samples, when the cyclostationary features are properly identified, this method can perform better than the energy based detection method. However the main drawbacks with this method are the complexity associated with the technique and the requirement of some a-priori knowledge of the primary user signal.

Here we provide some of the fundamentals of cyclostationary feature analysis and show how it can be used to detect primary users in the environment for cognitive radio networks.

A random process $x(t)$ can be classified as wide sense cyclostationary if its mean and autocorrelation are periodic in time with a period of T. Mathematically the mean and the autocorrelation are respectively given by,

$$E_x(t) = E_x(t + mT) \tag{17}$$

and

$$R_x(t, \tau) = R_x(t + mT, \tau) \tag{18}$$

where, t is the time, τ is the lag associated with the autocorrelation function, and m is an integer. The periodic autocorrelation function can be expressed in terms of the Fourier series given by,

$$R_x(t, \tau) = \sum_{\alpha=-\infty}^{\infty} R_x^{\alpha}(\tau) \exp(2\pi j \alpha t) \tag{19}$$

where,

$$R_x^{\alpha}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_T x(t + \frac{\tau}{2}) x^*(t - \frac{\tau}{2}) \exp(-2\pi j \alpha t) dt \tag{20}$$

The expression in (20) is known as the cycle autocorrelation, and for a cyclostationary process with a period T_0, the function $R_x^{\alpha}(\tau)$ will have component at $\alpha = 1/T$. Using the Wiener relationship, the Cyclic Power Spectrum (CPS) or the spectral correlation function can be defined as,

$$S_x^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau) \exp(-j2\pi f \tau) d\tau \tag{21}$$

The CPS in (21) is a function of the frequency f and the cycle frequency α, and any cyclostationary features can be detected in the cyclic frequency domain. An alternative expression for (21), for the ease of computing the CPS, is given by,

$$S_x^{\alpha}(f) = \lim_{T_0 \to \infty} \lim_{T \to \infty} \frac{1}{T_0 T} \int_{-T_0/2}^{T_0/2} X_T(t, f + \frac{1}{\alpha}) X_T^*(t, f - \frac{1}{\alpha}) dt \tag{22}$$

where, $X_T^*(t, u)$ is the complex conjugate of $X_T(t, u)$, and $X_T(t, u)$ is given by,

$$X_T(t, u) = \int_{t-T/2}^{t+T/2} x(v) \exp(-2j\pi u v) dv \tag{23}$$

Expression in (22) is also known as the time-averaged CPS which achieves the theoretical CPS. Figure-10 depicts an example of a CPS plot for BPSK modulated signal. In the figure N is the number of samples per block corresponding to the time interval T and M is the total number of blocks used for time averaging. The figure clearly depicts the cyclic frequency components centered at $\alpha = \pm 40$ MHz, and the additive noise component appearing at $\alpha = 0$. Therefore, using the CSD one could detect the presence of the primary user.

Now, we present how the CSD can be used to generate a test statistic to perform primary user detection. Considering the CSD to detect the primary user, we can re-write equation (7) with respect to the CSD as,

$$\begin{aligned} H_0 &: S_r^{\alpha}(f) = S_v^{\alpha}(f) \\ H_1 &: S_r^{\alpha}(f) = S_s^{\alpha}(f) + S_v^{\alpha}(f) \end{aligned} \tag{24}$$

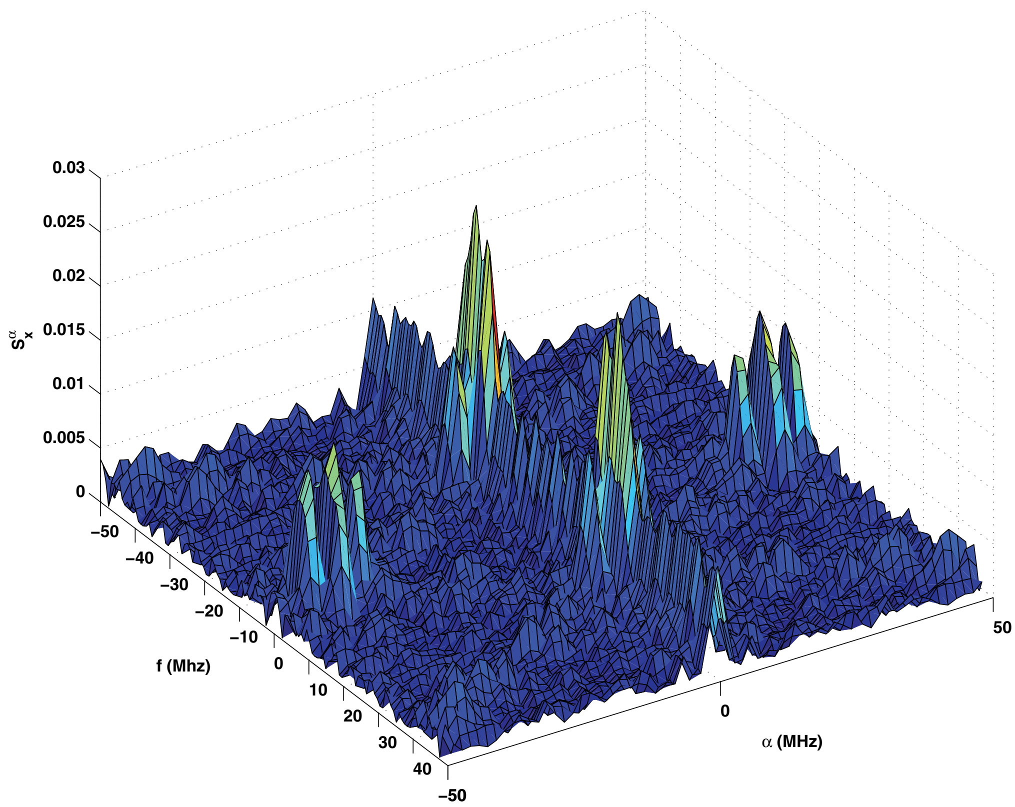

Fig. 10. Cyclic Spectral Density for BPSK with a signal to noise ratio of -13.3dB with $N = 50$ samples averaged over $M = 40$, with $f_c = 20$MHz center frequency and symbol rate of $R_b = 5$Mbps.

where, $S_\nu^\alpha(f)$ is the CSD of the additive noise $\nu(t)$, and $S_s^\alpha(f)$ is the CSD of the primary user signal $s(t)$. Since $\nu(t)$ is not a cyclostationary process, the CSD of ν for $\alpha \neq 0$ is zero. Based on this we can derive the test statistic for the detector in the discrete domain as,

$$\xi = \sum_{\alpha,\alpha\neq 0} \sum_f S_r^\alpha(f)\tilde{S}_r^\alpha(f) \tag{25}$$

where, $\tilde{S}_r^\alpha(f)$ is the conjugate of $S_r^\alpha(f)$. The detector is then given by,

$$d = \begin{cases} 0; \ \xi < \lambda \\ 1; \ \xi \geq \lambda \end{cases} \tag{26}$$

An important point to note here is that one needs sufficient number of samples (i.e. sufficient values for N and M) to get a good estimate of the CSD and hence this method is not so computationally efficient. Furthermore, when insufficient number of samples are used, the detection performance will tend to greatly degrade due to the poor estimate of the CSD.

5.4 Spectrum sensing with matched filter detection

The matched filter detection based sensing is the same as the traditional matched filter detection technique (Sklar, B.) deployed in traditional digital receivers. Obviously for match filter based spectrum sensing a complete knowledge of the primary user signal is required such as the modulation format data rate, carrier frequency etc. The matched filter detection technique is a very well treated topic in literature therefore we just present the fundamental results on matched filter detection in this section. Given a real transmit signal waveform $s(t)$ defined over $0 \leq t \leq T$ the corresponding matched filter maximizing the signal to noise ratio at the output of the filter sampler is given by,

$$h(t) = \begin{cases} s(T-t); & 0 \leq t \leq T \\ 0; & \text{elsewhere} \end{cases} \tag{27}$$

Figure-11 depicts matched filter based spectrum sensing method for primary user detection. Considering that a complete signal information of the primary user signal is required in this case the matched filter method is not really recommended by the system designers to suit our purpose here unless when the complete signal information is known to the secondary user. Then based on the test statistic $\xi(nT)$ at the output of the filter sampled every $t = nT$ seconds,

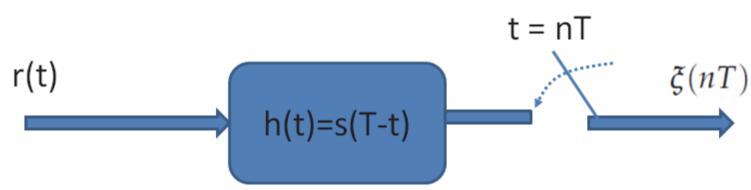

Fig. 11. Matched filter based spectrum sensing and detection of primary users.

the detector is given by,

$$d(nT) = \begin{cases} 0; & \xi(nT) < \lambda \\ 1; & \xi(nT) \geq \lambda \end{cases} \tag{28}$$

Performance wise matched filter based detector gives better detection probability compared to the previously discussed methods using the energy detector and the cyclostationary feature based detector.

5.5 Spectrum sensing in UWB radios with MB-OFDM

In many cases it is important to detect the primary users within a specific sub-band rather than in the entire band of operation. Since UWB spans a large portion of the spectrum we adopt a slightly different method to detect primary users in the particular bands of interest. Detecting a primary user in the entire band of operation can be performed using any of the methods specified for spectrum sensing in the previous sections. Here we consider detecting the primary user in a specific sub-band. Consider the FFT output of the MB-OFDM UWB receiver $y_j(i)$ corresponding to the j^{th} time sample in the i^{th} frequency bin with $i = 1, 2 \ldots N_{FFT}$. The primary user detection in the i^{th} frequency bin can be performed considering the energy detector (for example) using the test statistic given by,

$$\xi(i) = \sum_{j=1}^{N} y_j(i) y_j^*(i) \tag{29}$$

followed by the threshold detection as explained before. The primary user detection for the entire band can also be obtained by extending the above test statistic to derive a new test statistic given by,

$$\xi = \sum_{i=1}^{N_{FFT}} \sum_{j=1}^{N} y_j(i) y_j^*(i) \tag{30}$$

followed by the threshold detection. A hard-combining method for the primary user detection in the entire band could also be used on the other hand. In the hard-decision based combination method we can decide that a primary user is present if at least one of the N_{FFT} frequency bin had decided on H_1. In this case the detection rule becomes,

$$d = \bigwedge(d_i) \tag{31}$$

where, $\bigwedge$ is the logical 'OR' operation in the binary format and d_i are the decision outcomes for the i^{th} frequency bin. In this case we could also derive the detection and false alarm probabilities (for the 'OR' logic based hard decision rule) as,

$$P_D = 1 - [1 - P_D(i)]^{N_{FFT}} \tag{32}$$

$$P_{FA} = P_{FA}^{N_{FFT}}(i) \tag{33}$$

where $P_D(i)$ and $P_{FA}(i)$ are the detection and false alarm probabilities respectively for the i^{th} frequency bin.

5.6 Collaborative spectrum sensing

In the previous section we described the hidden terminal problem with primary user nodes located at a distance from the the sensing cognitive radio node. Exploiting the spatial domain for spectrum sensing is a way to solve the hidden terminal problem which we present here. Spatial domain spectrum sensing is performed by sensing the environment at different locations and by fusing the corresponding results to make a final decision whether a primary user is present or not. This could be done by cognitive radio nodes collaboratively sensing the environment and sharing the information with each other. In such sense there are two ways collaborative sensing could be performed 1) cooperative spectrum sensing with a centralized fusion center, and 2) distributed spectrum sensing with no centralized fusion center. Below we present them in detail.

5.6.1 Cooperative spectrum sensing

In cooperative spectrum sensing (Ganesan, G.; Mishra, S.) cognitive radio nodes in the environment sense the spectrum locally and then send the decision to a centralized node termed as the cognitive base station (CBS). The cognitive base station then would fuse the data and decide upon the presence of a primary user, the decision is then reported back to the cognitive radio nodes in a secure and reliable channel. Figure-12 depicts the cooperative spectrum sensing scenario which we describe here. Error prone reporting channels between the cognitive radios and the base station can also degrade the detection performance for the cooperative sensing as presented in (Aysal, T.). In this case however we assume error free channels for reporting the sensing data back and forth.
Let us assume there are K cognitive radio nodes present in the environment, and the $k^{th}, k \in \{1, 2 \ldots K\}$ cognitive radio node performs spectrum sensing using any of the one methods described in the previous sections (energy based method for example). If the corresponding hard decision made by the respective cognitive radio node is d_k, then the cognitive base station can perform its fusion using the 'OR' rule given by $\hat{d} = \bigwedge(d_k)$, where $\bigwedge$ is the logical 'OR' operator. The corresponding detection probability after data fusion then becomes,

$$P_D = 1 - [1 - P_D(k)]^K \tag{34}$$

$$P_{FA} = P_{FA}^K(k) \tag{35}$$

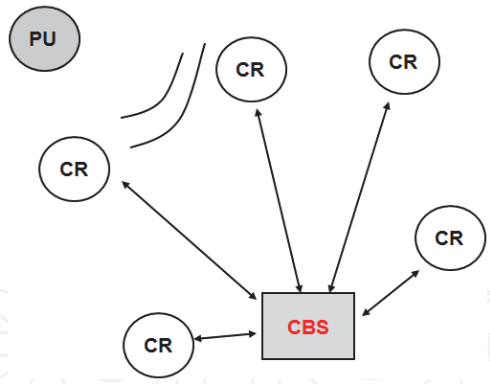

Fig. 12. Cooperative spectrum sensing with cognitive base station.

where $P_D(k)$ and $P_{FA}(k)$ are the detection and false alarm probabilities respectively for the local sensing performance at the k^{th} cognitive radio node. The fusion rule at the cognitive base station can be varied depending on the design requirements. One could also consider the logical 'AND' rule or in general the L out-of-K rule where you decide upon the presence of the primary user if L cognitive radio nodes have detected the presence out of the K nodes. Figure-13 depicts the performance curves in terms of the complementary ROC curves for the 'OR' rule base cooperative sensing with energy based local decisions. From the figure we clearly see a great improvement in the detection performance when fusion strategy is deployed with cooperative sensing compared to the non-cooperative sensing case, especially at low signal to noise ratio levels.

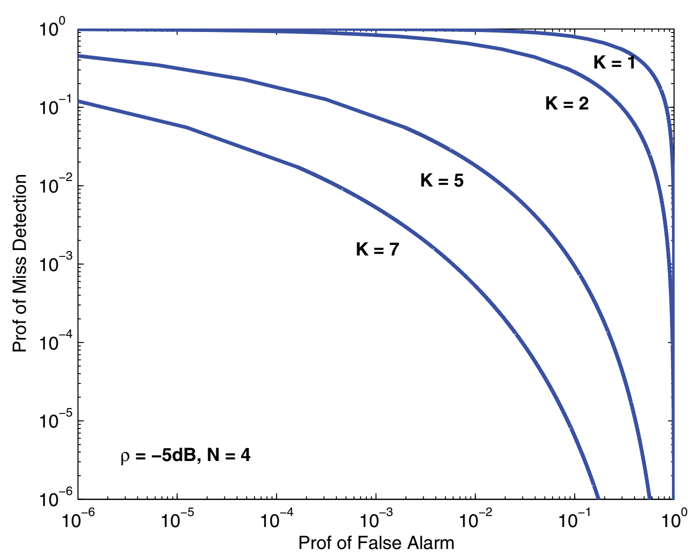

Fig. 13. C-ROC curves for the cooperative spectrum sensing with the 'OR' rule based fusion decision at the CBS, with $\rho_k = \rho = -5$dB and $N_k = N = 4$.

The data fusion can also be performed by means of soft combination. In soft combination the cognitive radio nodes will report the soft decisions to the cognitive base station and the base station would fuse the soft decisions by appropriate methods. Some of the standard techniques considered for soft-fusion are the equal ratio combining and the maximal ratio combining. In equal ratio combining the received soft decisions are summed up at the base station and a threshold detection is performed to make the decision. In the maximal ratio combining the soft decisions from the k^{th} cognitive radio node is weighted appropriately based on its credibility for example and then summed up before performing the threshold detection.

5.6.2 Distributed spectrum sensing

The other collaborative technique in spectrum sensing is the distributed sensing method (Bazerque, J.; Chen, Y.). In distributed sensing unlike in the cooperative sensing there is no fusion center to perform the data fusion. Instead the locally sensed data are exchanged between the cognitive radio nodes themselves in the environment and the cognitive radio nodes will perform the fusion locally with the collected information. The information exchange between the cognitive radios can be by means of broadcasting or by means one to one transmissions. Figure-14 depicts an example of the collaborative sensing strategy.
Similar to the cooperative sensing case, here too the local sensing can be performed by one of the proposed techniques for spectrum sensing in the previous sections. Instead of performing the data fusion at the base station as in the cooperative sensing strategy it is performed at the cognitive radio nodes itself in this case. The major advantage associated with distributed sensing is the non-requirement of a central fusion center and the corresponding feedback reporting channel from the base station to the cognitive radio nodes. However, distributed sensing increases the overhead at the nodal level by requiring to perform the data fusion and data management etc.

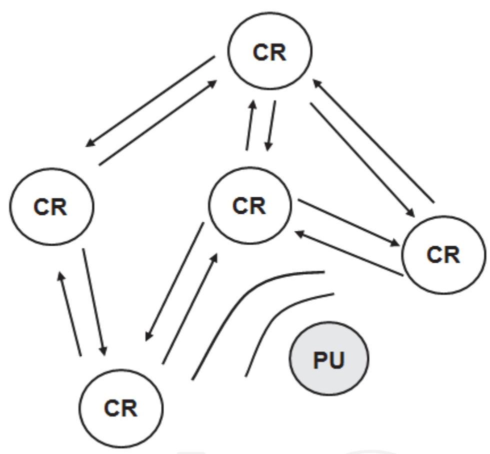

Fig. 14. Distributed spectrum sensing without a centralized fusion center.

6. Interference mitigation with detect-and-avoid techniques

The interference mitigation problem can be classified as interference caused to the cognitive radio nodes from the primary users as well as the secondary users and the interference caused by the cognitive radio nodes to the primary users and other secondary users. The interference actually depends on the geographical positioning of the radio nodes (that is the distance between the nodes), the transmit signal power from a particular node, and the channel gains of the links etc. In this section we briefly touch upon interference mitigation by means of detect-and-avoid in MB-OFDM UWB radios.
As described in the previous sections, there is a potential risk for wireless interferences of UWB technology with other wireless devices; in particular with WiMAX Customer Premise Equipment (CPE). In (Rahim, A et. al.) and (Li, Y. et. al.) the coexistence and interference issues mentioned here have been investigated to some extent. To address the risk of

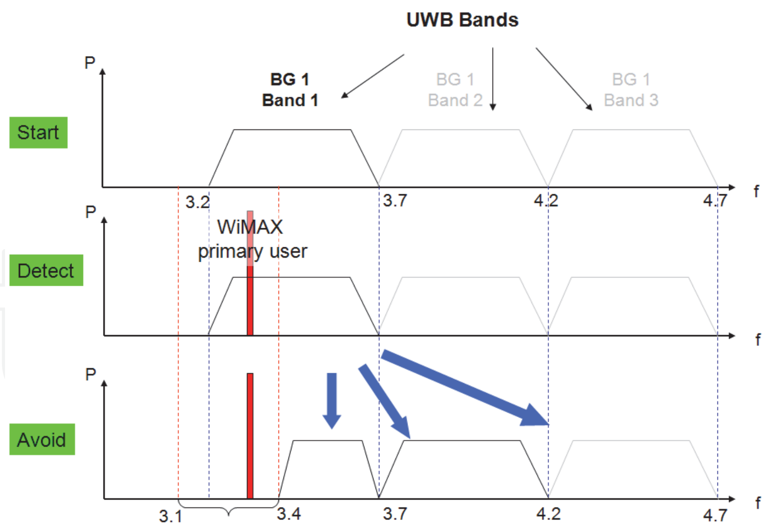

Fig. 15. Detect and Avoid of an UWB device to avoid interference to a WiMAX primary wireless service

interference of UWB on other wireless services, regulatory bodies around the world have defined stringent limits for the emission power of UWB devices. In most cases the limit is given as an Equivalent Isotropically Radiated Power (EIRP) emission mask. EIRP emission mask was defined by the FCC in 2002, the European Union in 2006, China in 2008, Japan in 2006 and Korea in 2006. The disadvantage of the EIRP mask is that UWB transmission power is limited even in the absence of WiFi or WiMAX communication. A more flexible approach is to allow higher emission power for UWB devices when no other wireless system is transmitting within the same coverage area.

In this case an opportunistic approach could be used, where secondary users (e.g., UWB devices) are required to detect the transmission of primary users in specific spectrum bands and consequently refrain from transmitting in those bands or reduce their emission power. In the case of UWB, this approach is also named Detect and Avoid (DAA) as UWB devices should *Detect* the presence of a primary user (e.g., WiMAX) in the radio frequency spectrum environment and use other frequency bands for the transmission to *Avoid* creating interference to the primary user (see Figure-15). In this context, UWB DAA can be considered a simple form of cognitive radio.

Regulations for the use of the DAA mitigation techniques for UWB are different around the world. In Europe, the regulation for generic UWB devices (i.e., not specifically DAA enabled) is composed of two ECC Decisions: the baseline Decision ECC/DEC/(06)04 (ECC Decision, 2006), which defines the European spectrum mask for generic UWB devices without the requirement for additional mitigation and Decision ECC/DEC/(06)12 (ECC Decision, 2006), recently amended by (ECC Decision, 2008), which provides supplementary mitigation techniques such as Low Duty Cycle (LDC) or DAA. The related European Commission decision is 2009/343/EC (EC Decision, 2009).

In USA, FCC (FCC Part47-15, 2007) has opened the 3.1 - 10.6 GHz frequency band for the operation of UWB devices provided that the EIRP power spectral density of the emission is lower than or equal to -41.3 dBm/MHz. FCC regulations do not specify the use of mitigation techniques for UWB devices operating in the mentioned frequency range.

In China Mainland, in the 4.2-4.8 GHz band, the maximum EIRP is restricted to -41.3dBm/MHz by the date of 31st Dec, 2010. After that, the UWB devices shall adopt an

Interference Relief Technology, such as DAA. There are no specific parameters or limit values for DAA in the current Chinese UWB regulation specification.

In Japan, in the 3.4 to 4.8 GHz frequency range, UWB devices without interference avoidance techniques such as DAA may not transmit at a level higher than -70 dBm/MHz. In the 3.4 to 4.2 GHz band, UWB devices may transmit at or below the limit of -41.3 dBm/MHz, under the condition that they are equipped with interference avoidance techniques such as DAA. In the 4.2 to 4.8 GHz band, UWB devices shall adopt an interference avoidance technique after 31st Dec, 2010.

In Korea, the UWB emission limit mask requires the implementation of an interference avoidance technique such as DAA in the 3.1 to 4.2 GHz and 4.2 to 4.8 GHz bands to provide protection for IMT Advanced systems and broadcasting services. The requirements in the 4.2 to 4.8 GHz band shall be implemented after 31st Dec, 2010.

In Hong Kong, the proposed rule is, based on the 33rd Radio Spectrum Advisory Committee (RSAC) Meeting discussion, to allow a maximum EIRP of -41.3 dBm/MHz in the 3.4 to 4.8 GHz band, provided that appropriate mitigation techniques are employed. Otherwise the maximum EIRP is restricted to -70 dBm/MHz.

In Europe, references (ECC Report 120, 2008) and (EC Decision, 2009) identify three types of victim systems to be protected by DAA mechanisms: 1) BWA Indoor terminals in the 3.4 - 4.2 GHz range, 2) Radiolocation systems in the 3.1 - 3.4 GHz range and 3) Radiolocation systems in the 8.5 - 9 GHz range.

The DAA mitigation techniques are based on the concept of *coexistence zones* which correspond to a minimum isolation distance between an UWB device and the victim system. For each DAA zone, in conjunction with the given minimum isolation distance, the detection threshold and the associated maximum UWB transmission level are defined based on the protection zone the UWB device is operating within. In the frequency range 3.4 - 4.2 GHz, three zones are defined on the basis of the detected uplink power of the victim signal: Zone 1 with a detection threshold for the uplink victim signal of -38 dBm. In this zone, the UWB device is required to reduce its emission level in the victim bands to a maximum of -80 dBm/MHz. As an alternative, the UWB device is allowed to move to a non-interfering channel. Zone 2 with an uplink detection threshold of -61 dBm. In this zone, the UWB device is required to reduce its emission level to a maximum of -65 dBm/MHz. As an alternative, the UWB device is allowed to move to a non-interfering channel. Zone 3 where the UWB device does not detect any victim signal transmitting with a power greater than -61 dBm. In this case, the UWB device is allowed to continue transmitting at maximum emission level of -41.3 dBm/MHz. Figure-16 provides a description of the different protection zones:

Reference (ECC Report 120, 2008) provides flowcharts for the implementation of the DAA algorithm as represented in Figure-17.

The flowcharts and detection algorithms are implemented on the basis of the following parameters:

- Minimum Initial Channel Availability Check Time, which is the minimum time the UWB device spends searching for victim signals after power-on.
- Signal Detection Threshold, which is the victim power level limit, employed by the UWB device in order to initiate the transition between adjacent protection zones.
- Avoidance Level, which is the maximum Tx power to which the UWB transmitter is set for the relevant protection zone.
- Default Avoidance Bandwidth, which is the minimum portion of the victim service bandwidth requiring protection.

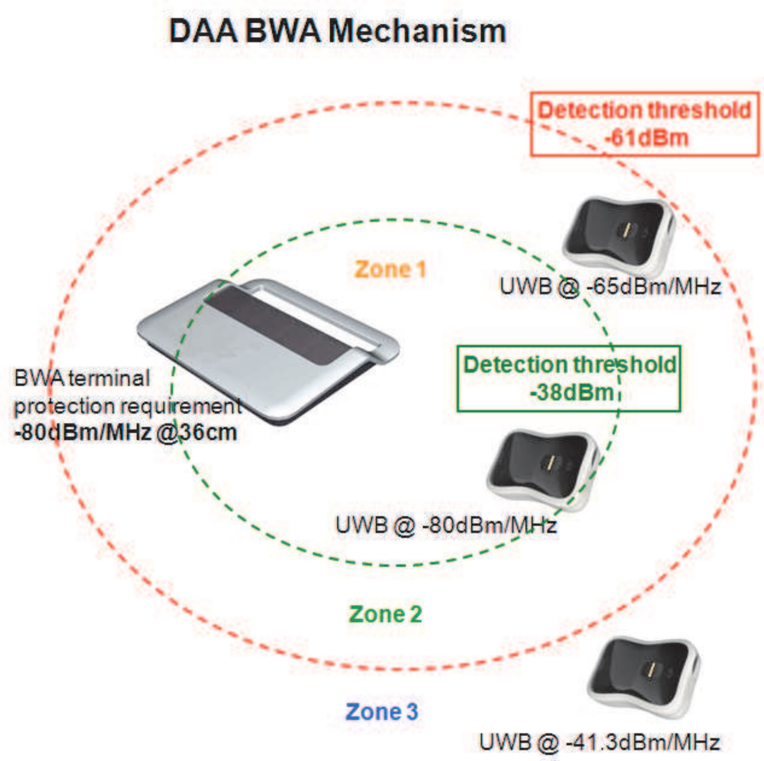

Fig. 16. Protection zones for DAA UWB devices

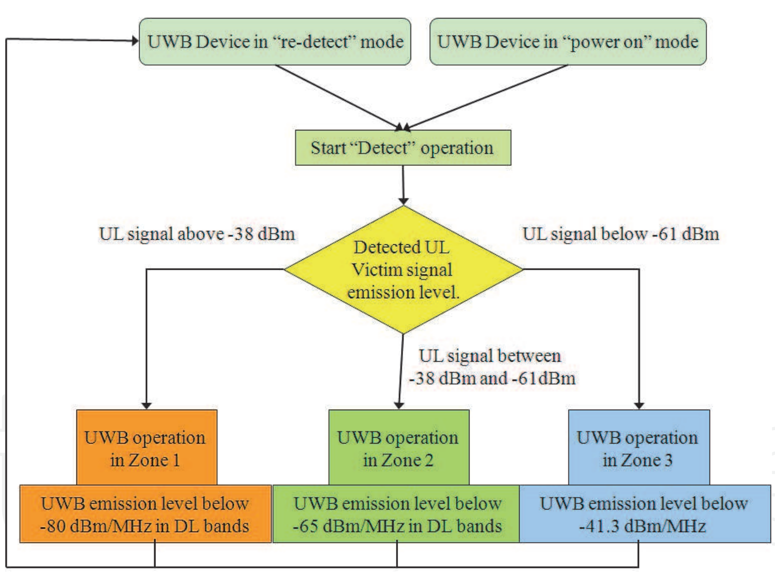

Fig. 17. Workflow of Detect and Avoid for three protection zones

- Maximum Detect and Avoid Time, which is the maximum time duration between a change of the external RF environmental conditions and adaptation of the corresponding UWB operational parameters.
- Detection Probability, which is the probability for the DAA enabled UWB device to make a correct decision either due to the presence of a victim signal before starting transmission or due to any change of the RF configuration during UWB device operation.

These parameters are also dependent on the type of communication service provided by the primary user. For example, UWB devices have different DAA times for different services (e.g., VoIP, Web surfing, Sleep mode, Multimedia broadcasting) of the primary user (e.g., Broadband Wireless Access).

In UWB networks, devices can negotiate detection capability and share detection information. For example, if one device is sending a large file to another device, it is possible for the receiving device to be the primary detecting device. DAA UWB network can implement smart detection algorithms where the most capable or powered devices can implement the detection of the primary users and distribute this information to the less capable devices.

7. Localization and radio environment mapping

For the cognitive radio nodes to perform its functionalities properly it needs to have context aware capabilities such as the spectrum sensing capability. Another context aware mechanism to support the intelligence of the cognitive radio is locating radios in the network (Giorgetti, A.). By means of localizing the radios in the network the cognitive radio node can create a map of radios which would help to perform its functionalities better. For example, knowing the location of the primary user nodes can become beneficial when considering directional transmissions for maximizing the spatial re-usage of the spectrum.

Another means getting context awareness is by means of radio environment maps. The term radio environment map or REM refers to a database of the radio environment, which can be locally maintained in a node or in a network where all the nodes could access it. A cognitive radio node in a network can get its intelligence by means of sensing or extracting information from the REM. The REM itself need to be updated periodically by means of sensing and learning operations. The advantage of maintaining a network level REM is that not all the nodes need to perform sensing on its own but rather get information from the REM and hence reducing the complexity of the cognitive radio node. A typical REM would contain information about the radio nodes in the vicinity and the related radio and network resources such as frequency channels, data rates, center frequency, location information, which network the node belongs to, what services the node offers, the regulatory and policy details of the nodes, and the nodes historical behavior etc. Getting and maintaining all the information about the nodes in the environment is not always feasible in which case the REM will contain only the information that are available. By using such REM data bases communication networks can be made much efficient especially considering wireless networks. However, many technical aspects related to the design and deployment of REM need to be addressed. For example, how often the information need to be updated in the REM, how much and what information required to be stored, what are the overheads in having such REM for maintaining and distributing the information, and finally the security and privacy requirements for the REM.

8. Scenarios and applications for UWB based CR

Finally, we present some application scenarios for the use of UWB based cognitive radios. The scenarios that we present here are derived from the two EU projects C2POWER (C2POWER, 2010) and EUWB (EUWB, 2008). The scenarios that we provide are for dynamic spectrum access (EUWB scenarios) as well as for energy efficient communications (C2POWER scenario).

Scenario-1: UWB based cognitive radios are considered for home entertainment where UWB based multimedia devices such as a hi-fi surround system with audio/video transmissions

could utilize the DAA techniques. In such an environment the UWB devices need to be aware of the 5GHz ISM band devices, WiMAX devices in 3.6GHz etc.
Scenario-2: UWB based cognitive radios are considered for airborne in-flight transmissions such as for audio/viedo delivery to the passengers. In such scenarios the UWB radios need to be aware of any custom built radios within the UWB frequency band for flighth specific applications and as well as any satellite receivers in the UWB frequency range.
Scenario-3: UWB based cognitive radios are considered for vehicular communications such between sensors and the central unit. In such situations the UWB radios need to be aware of the surrounding radios in order to avoid interference and at the same time make sure that its time critical transmissions are also not interfered with.
Scenario-4: UWB radios can also be used for energy saving in short range wireless communications. Given the favorable channel conditions a source node may opt to communicate to its destination by means of a relay node for better energy efficiency (C2POWER, 2010). In such context UWB radios with intelligence (i.e. UWB based cognitive radios) can play a prominent roll.

9. Conclusion

In this chapter we provided the concept and fundamentals of UWB based cognitive radios for having intelligence in the standard UWB radios. By having cognition in the UWB devices the transmissions could be dynamically adopted in order to improve the performance. The intelligence in the radio leads to a better usage of the radio resources such as the radio spectrum by having dynamic spectrum access capabilities in the spatio-temporal domain. The cognitive engine residing in the UWB radio learns about its surrounding and acts based on the internal and network level policies.
Even though the cognitive radio technology shows prominent advantages yet many issues are to be solved prior to its deployment, various standardization and regulatory activities are currently underway in order to regulate the dynamic spectrum access and cognitive radio technology.

10. Acknowledgement

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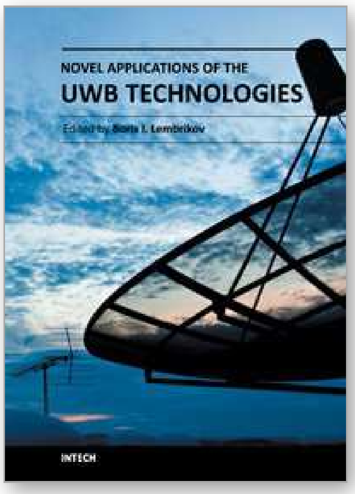

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Ultra wideband (UWB) communication systems are characterized by high data rates, low cost, multipath immunity, and low power transmission. In 2002, the Federal Communication Commission (FCC) legalized low power UWB emission between 3.1 GHz and 10.6 GHz for indoor communication devices stimulating rapid development of UWB technologies and applications. The proposed book Novel Applications of the UWB Technologies consists of 5 parts and 20 chapters concerning the general problems of UWB communication systems, and novel UWB applications in personal area networks (PANs), medicine, radars and localization systems. The book will be interesting for engineers and researchers occupied in the field of UWB technology.