FLEXIBLE DISTRIBUTED WIDEBAND COGNITIVE RADIO NETWORK WITH DOUBLE THRESHOLD ENERGY DETECTOR COMBINING COOPERATIVE AND SPATIAL DIVERSITY

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ABSTRACT

To improve the radio spectrum utilization, cognitive radio (CR) technology, which can dynamically use frequency bands detected as free, has been proposed. To provide this detection with sufficiently security for the licensed primary user (PU) and without a loss of CR capacity, spectrum sensing is a fundamental requirement in CR. Also, if this spectrum sensing is addressed for wideband, a current idea is to distribute it among all CRs in the network by dividing the wideband sensing into several sub-bands sensing. However, this physical spectrum division can be too wide to detect narrow band PU. In this paper, we propose to analyse digitally these sub-bands by using a numerical fast Fourier transform (FFT). This analysis is then made, in each sub-sub-bands, by a double threshold energy detection method. For a targeted probability of PU detection, simulation results show the possibilities of the proposed system when a multi-optimization problem is addressed.

1. INTRODUCTION

Current wireless communication networks are designed with inflexible rules in order to operate in a given time slot over a fixed frequency range and within certain area. Cellular concept is probably the most illustrating example. Although all the current usable frequency bands are already affected, studies have found that the utilization of a large part of these bands is very low. In order to improve spectral allocation, cognitive radio (CR) [1] has been proposed as a potential future wireless communication system, which enables a new class of mobile terminals to change their transmission parameters by spectrum sensing. In fact, in contrast to current systems where the spectrum allocation is static, future CR devices will be able to seek and use the frequencies in a dynamic way for network access; this will be done by spectrum sensing which consists in autonomous rapid detection of vacant bands in the radio spectrum.

Spectrum sensing techniques can be classified among three categories: matched filter with coherent detection [2], energy detector [3], and feature detection [4], [5]. When an energy detector is used, the hidden terminal problem caused by shadowing or deep primary user (PU) fading has to be counteracted by using diversity. There are different ways to obtain diversity in energy detection. On the one hand, if the spectrum sensing is realized with one CR, multiple antennas permit to maintain a high probability of detection. On the other hand, another spectrum sensing scheme consists in using a fusion center (FC) that collects the spectrum measurements from multiple CRs. This method is called cooperative spectrum sensing. Although the cooperative spectrum sensing in narrowband has been widely studied in the literature [6]-[8], the wideband spectrum sensing (WSS) is not often considered.

Wavelet approach was thus developed in [9], where the WSS is conducted with an estimated power spectral density in each subband (SB). The main drawback of this method is that the authors proposed PU detection by using one CR, that leading to a critical spectrum sensing time. In [10], a WSS is proposed. Called multi-bands joint detection, it jointly detects the signal energy levels over multiple frequency bands rather than consider one band at a time. Recently, a cooperative shared spectrum sensing has been proposed [11] where the wideband is divided into several sub-bands. The authors propose a framework designed to minimize uncertainty in PU detection, while maintaining control over the amount of energy spent and spectrum sensing time. But the main drawback of this method concerns the number of necessary analysed SBs and/or CRs, which can be extremely large if an important WSS is devoted. In fact, the larger band, the more SB should be necessary. It can result to a very high number of required CRs and/or spectrum sensing time to maintain sufficient PU protection in each SB.

In this paper, we propose a distributed wideband spectrum sensing as in [11], but we digitally divide the SBs by using a numerical fast Fourier transform (FFT), which creates sub-SBs (SSB). Furthermore, we use a double threshold energy detector. The proposed flexible architecture could permit to keep a moderate number of SB and so a moderate number of CRs, while maintaining a sufficient PU protection and an efficient spectrum sensing time. Computer simulations show that for a 100 MHz SB channel, when the frame duration is 1*ms*, we can maintain a detection probability of 90% and a low loss of available bandwidth for a spectrum sensing time equals to 10% of the frame duration and for several SSB wide.

The paper is organized as follows: Section 2 presents the distributed WSS method; Section 3 is devoted to the core of the proposed flexible WSS with double threshold energy detector; Section 4 analyses the system performances through simulation results; finally Section 5 concludes the work.

2. DISTRIBUTED SPECTRUM SENSING

Generally, we consider that a frequency band as free when this band is only composed of noise. In the opposite case, if the filtered signal is composed of noise in addition to an unknown PU signal, the frequency band is considered as occupied. In practice, this signal detection can be performed using a hypothesis test.

2.1 Wideband Spectrum

We suppose a spectrum sensing in a wideband W, which is composed of L primary users. $\Delta f_{\min}$ denotes the minimum frequency space between two adjacent PUs. If we assume that the primary users do not occupy the entire bandwidth, then some of the free bands could be available for being used by CR (Fig. 1). These free bands can be detected by using CR network (CRN).

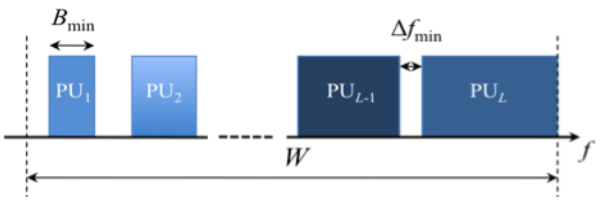

Figure 1 – Available frequency SBs in a wideband spectrum

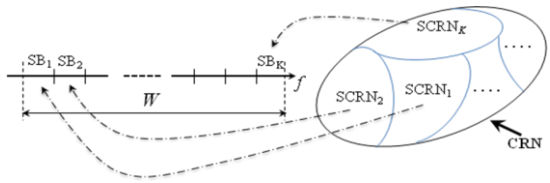

Figure 2 – Distributed wideband among the different SCRN

2.2 Spectrum sensing distribution

The detection performance of conventional spectrum sensing based on energy detector is usually perturbed by the propagation channel characteristics between PUs and CRs which performed the detection. In fact, PU signal can be attenuated by a deep fading, which can bring missed detections. In such scenarios, spatial diversity at each CR and/or cooperative CR devices would increase the probability of PU detection by sharing their different spectrum sensing measurements. However, the larger the spectrum sensing, the longer the time detection, to obtain detection probability close to one. A solution consists in dividing wide spectrum in many bands called SB.

To detect free bands in a wideband spectrum, cooperative distributed spectrum sensing, which consists in affecting a sufficient number of CRs to sense a part of the wideband spectrum, can be used. The set of affected CRs is called a sub-cognitive radio network (SCRN) (Fig. 2).

In this case, W is divided in K SB, and we have:

$$\mathrm{SB}_p \cap \mathrm{SB}_q = \varnothing, \text{if } p \neq q \text{ and } W = \bigcup_{k=1}^{K} \mathrm{SB}_k \tag{1}$$

$$(\mathrm{SCRN}_p) \cap (\mathrm{SCRN}_q) = \varnothing, \text{if } p \neq q \tag{2}$$

$$\mathrm{CRN} = \bigcup_{k=1}^{K} (\mathrm{SCRN}_k) \tag{3}$$

where SB_k denotes the kth SB analyzed by the SCRN_k (k^{th} SCRN). The width of the sensed band in each SCRN is: $\Delta f = W/K$.

3. FLEXIBLE WIDEBAND SPECTRUM SENSING COGNITIVE RADIO

3.1 Sensed signal model

We suppose that each SCRN is composed of M CRs and N_m denotes the number of antennas used by the mth CR. We consider a channel environment composed of P_m^l multi-paths where $h_i^{l,m}(p)$ represents the discrete-time channel impulse response between the lth PU and the ith receive antenna of the mth CR. p refers to the pth multi-path of the propagation channel. Thus, the base band received signal from the lth PU at the ith antenna can be written as:

$$r_i^{l,m}(n) = \sum_{p=0}^{P_m^l - 1} h_i^{l,m}(p) s^l(n-p) + b_i(n) \tag{4}$$

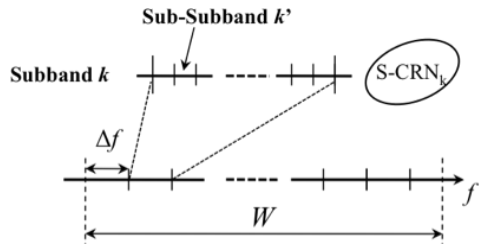

Figure 3 – Sub-band division

where $s^l(n)$ represents the lth PU transmitted complex signal at time n and $b_i(n)$ is an additive complex Gaussian noise with zero mean and variance $\sigma_{b_i}^2$.

Without loss of generality, the PU signal and the noise are assumed to be independent to each other and $\forall i, \sigma_b^2 = \sigma_{b_i}^2$. In the following, we focus our interest on the kth SB of width Δf, sensed by the ith receive antenna of the mth CR.

3.2 Flexible SSB energy detection

Contrary to [11], we divide the kth SB in K' SSB, by using a K' points ($K' >> P_m^l$) fast Fourier transform (FFT) (see Fig. 3). It enables to better take multipath fading environment into account and offers the possibility to optimize the free band detection, if an active PU exists in the kth SB, with a signal bandwidth lower than Δf.

In order to take a decision on the k'^{th} SSB availability, the FFT of the received signal (4) can be computed, and we obtain in the k'^{th} SSB:

$$\begin{aligned} R_i^{l,m}(k') &= \frac{1}{\sqrt{K'}} \sum_{n=0}^{K'-1} r_i^{l,m}(n) e^{-j2\pi \frac{k'n}{K'}} \\ &= H_i^{l,m}(k') S^l(k') + B(k') \end{aligned} \tag{5}$$

with

$$H_i^{l,m}(k') = \frac{1}{\sqrt{K'}} \sum_{n=0}^{K'-1} h_i^{l,m}(n) e^{-j2\pi \frac{k'n}{K'}} \tag{6}$$

where $S^l(k')$ corresponds to the PU signal transmitted over the k'^{th} SSB, $H_i^{l,m}(k')$ denotes the discrete frequency response of the propagation channel and $B(k')$ represents the received noise in the frequency domain. As normalized FFT is a linear operation, the random variables $\{B(k')\}$ are independent normally distributed with zero mean and variance σ_b^2 .

The k'^{th} SSB gain is assumed to be constant during the detection interval T_{DI} and we have:

$$H_i^{l,m}(k',t) = H_i^{l,m}(k') \text{for } \; 0 \le t \le T-1 \tag{7}$$

where $T_{DI} = T \dfrac{1}{\Delta f'} = T \dfrac{K'}{f_s}$. f_s denotes the sampling frequency of the received signal, T is the number of collected samples in each SSB and $\Delta f'$ denotes the wide of the sensed SSB.

3.3 Spatial spectrum sensing based on energy detector with double threshold

To decide whether the k'^{th} SSB is free or not, we test the classic following binary hypothesis on each receive antenna:

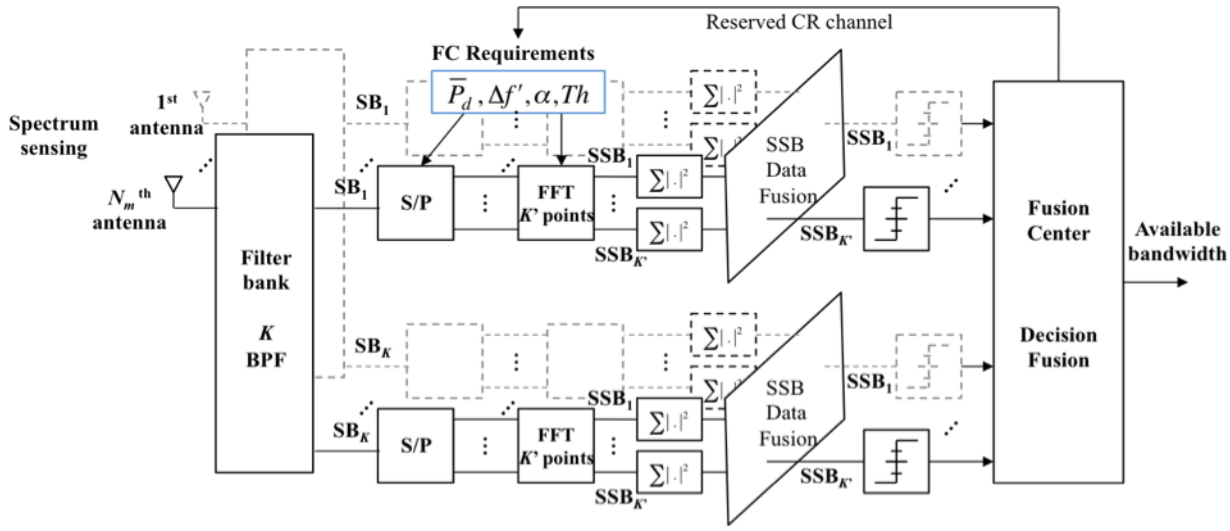

Figure 5 – Proposed CR architecture

$$\begin{cases} H_{0,k'} & R_i^{l,m}(k') = B(k') \\ H_{1,k'} & R_i^{l,m}(k') = H_i^{l,m}(k')S^l(k') + B(k') \end{cases} \quad (8)$$

We suppose a sensing spectrum time which makes it possible to collect T samples of the received signal in each SSB. Thus, we compute the received signal energy measured on the k'^{th} SSB for the ith receive antenna of the mth CR:

$$E_i^{l,m}(k') = \frac{1}{T}\sum_{t=1}^{T}\left|R_i^{l,m}(k',t)\right|^2 \quad (9)$$

To exploit the spatial diversity at the mth CR, we combine the received signal energy collected from each antenna and we have:

$$E^{l,m}(k') = \frac{1}{\sqrt{N_m}}\sum_{t=1}^{T}E_i^{l,m}(k') \quad (10)$$

According to the central limit theorem, for large T, $E^{l,m}(k')$ is asymptotically normally distributed with means [12]:

$$\begin{cases} H_{0,k'}: & \mu_{0,k'} = \sqrt{N_m}\,\sigma_b^2 \\ H_{1,k'}: & \mu_{1,k'} = \sigma_b^2 \dfrac{1}{\sqrt{N_m}}\displaystyle\sum_{i=1}^{Nm}\left(1+\frac{\left|H_i^{l,m}(k')\right|^2\sigma_s^2}{\sigma_b^2}\right) \end{cases} \quad (11)$$

and variances:

$$\begin{cases} H_{0,k'}: & \sigma_{0,k'}^2 = \dfrac{1}{T}\sigma_b^4 \\ H_{1,k'}: & \sigma_{1,k'}^2 = \dfrac{1}{T}\sigma_b^4\left(1+2\dfrac{\sigma_s^2}{\sigma_b^2 N_m}\displaystyle\sum_{i=1}^{N_m}\left|H_i^{l,m}(k')\right|^2\right) \end{cases} \quad (12)$$

where σ_s^2 represents the PU signal power.

The conventional binary test consists, for the mth CR, in deciding whether l^{th} PU in the k'^{th} SSB is present or not.

If $\varepsilon_{k'}$ represents the decision threshold for the k'^{th} SSB, the probability of false alarm $P_{fa}^m(\varepsilon_{k'}, T, N_m)$ and the probability of detection $P_d^m(\varepsilon_{k'}, T, N_m)$ are defined as:

$$\mathrm{P}\left(E^{l,m}(k') > \varepsilon_{k'}\middle|H_{j,k'}\right) = Q\left(\frac{\varepsilon_{k'} - \mu_{j,k'}}{\sigma_{j,k'}}\right) \quad (13)$$

for $j = 0$ and $j = 1$ respectively and where Q is the Q-function.

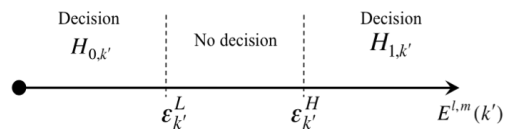

Figure 4 – Double threshold energy detector for the k'^{th} SSB (Decision Fusion)

To optimize the probability of false alarm under required probability of detection, double threshold judgment, as in [13], is used (Fig. 4). $\varepsilon_{k'}^L$ and $\varepsilon_{k'}^H$ are the lower and the higher decision threshold respectively.

This method is completed by the use of a FC, which collects cooperatively the CR local decisions and makes a final decision for the SCRN_k.

Following [13], decision fusion method is so used, and different rules can be employed to make the final decision. We use "Logic-OR" rule and the cooperative probability of detection Q_d can then be written:

$$Q_d = 1 - \prod_{m=1}^{M}\left(1 - \overline{P}_d^m\right) \quad (14)$$

where $\overline{P}_d^m$ is the target detection probability for the mth CR of the SCRN_k. By considering $\overline{P}_d^1 = ... = \overline{P}_d^m = \overline{P}_d$, the target detection probability is:

$$\overline{P}_d = 1 - \sqrt[M]{1 - Q_d} \quad (15)$$

The same reasoning makes it possible to express the cooperative probability of false alarm Q_{fa}.

When local decision is not sufficient enough, so that any decision can be made by the FC for some SSB, data fusion method described in [13] can also be applied. FC needs then to collect also energy values of SSBs which satisfy $\varepsilon_{k'}^L \le E^{l,m}(k') \le \varepsilon_{k'}^H$.

Finally, the proposed CR architecture is presented Fig. 5.

3.4 Multi-optimization problem

The choice of the threshold leads to a trade-off between the probability of false and the probability of missed detection. Deploying our CRN implies that a multi-optimization problem has to be solved. The main objective is a probability of detection close to 1 subject to the available throughput CRN is maximal.

The time used for spectrum sensing influences the network throughput and the lifetime of the CRN. Hence optimizing the spectrum sensing time can increase the throughput performances of the CRN. As we suppose that a narrow band PU signal can be active in a SB, the proposed detection performs a FFT in each of them. It allows maintaining a low probability of false alarm, but the SSB spectrum sensing time increases. Thanks to the double threshold energy detector, T can be adjusted. In fact, for a target detection probability $\overline{P}_d$ and given a low probability of false alarm $\overline{P}_{fa}^{low}$, with (13) by cancelling out the threshold variable, the minimum number of samples for spectrum sensing is given by:

$$T = \frac{N_m}{\left(P^m(k')\right)^2}\left(Q^{-1}\left(\overline{P}_{fa}^{low}\right) - Q^{-1}\left(\overline{P}_d\right)\sqrt{1+\frac{2}{N_m}P^m(k')}\right)^2 \qquad (16)$$

where $P^m(k') = \sum_{i=1}^{N_m} \frac{\left|H_i^{l,m}(k')\right|^2 \sigma_s^2}{\sigma_b^2}$.

We assume that the frequency allocation of the L PU is constant during a time T_c. We can also define

$$\alpha = \frac{\left(T_c - T_{DI}\right)}{T_c} = \frac{\left(T_c - \frac{TK'}{f_s}\right)}{T_c} = \frac{\left(T_c - \frac{TK'K}{W}\right)}{T_c} \qquad (17)$$

which represents the spectrum sensing time efficiency. If we suppose, to have a high Q_d and a low Q_{fa}, the available throughput of the CRN can be approximated [16] as follows:

$$Th_{k,m} \approx \alpha W_k^a (1-Q_{fa}) \log_2\left(1+SNR_{CRm}\right) P\left(H_{0,k}\right) \qquad (18)$$

where SNR_{CRm} denotes the mth CR signal to noise ratio and $P\left(H_{0,k}\right)$ the probability for which the primary users are inactive in SB_k. $W_k^a = (1-\Delta W_k)\Delta f$ represents the available detected bandwidth in SB_k and ΔW_k is called the normalized loss of bandwidth. Thus the total available CRN throughput for the mth CR is

$$Th_m = \sum_{k=1}^{K} Th_{k,m} \qquad (19)$$

So, the multi-optimization problem consists in solving the following system:

$$\forall k: \max_{T,K',M} Th_m = \sum_{k=1}^{K} Th_{k,m}$$
$$\text{s.t.} P_d(\varepsilon_{k'}, T, N_m) \geq \overline{P}_d \qquad (20)$$

According to SB sensing, to solve (20), FC could adjust some parameters, such as the minimal width of SSB, the number of CRs in the SCRN and the double threshold width. By holding α parameter constant, it is possible to have different accuracies on each SSB of the SB. Nevertheless, it will be necessary to adjust the number of CRs in the different SCRN in order to keep a high CRN throughput and a detection probability higher than a given threshold. However, if the CR available throughput is not an objective, double threshold could be adjusted without the need to increase the number of CRs in the SCRN. Simulation results show the possibilities of the proposed system when the multi-optimization problem (20) is addressed.

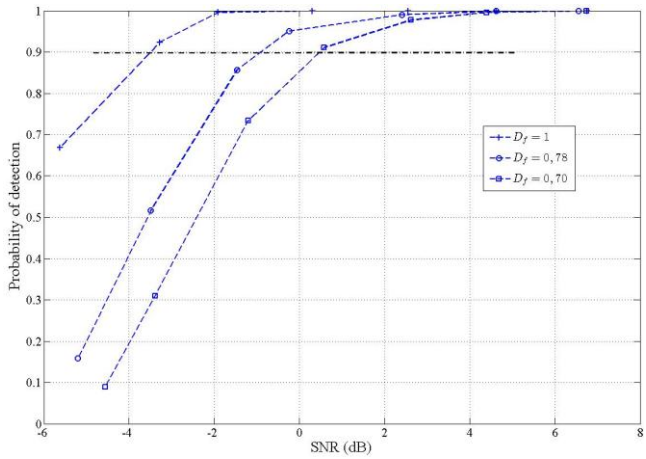

Figure 6 – Probability of detection versus average PU SNR ($Q_{fa} = 0.05$, $\Delta\varepsilon = 0.05$, $M = 5$ CRs in the SCRN)

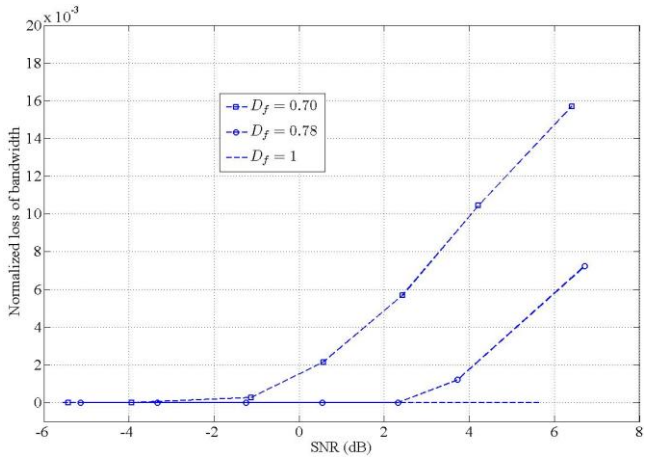

Figure 7 – Normalized loss of bandwidth versus average PU SNR ($Q_{fa} = 0.05$, $\Delta\varepsilon = 0.05$, $M = 5$ CRs in the SCRN)

4. SIMULATION RESULTS

The simulation parameters are the following. The sensed spectrum has a bandwidth W = 3GHz. We suppose that each CR is equipped with N_m = 2 antennas and with a filter bank composed of K = 30 band pass filters, so we have Δf = 100MHz.

We suppose that two primary users are present in the analyzed SB. PU use QPSK modulator, and the propagation channel between PU and the SCRN is composed of $P_m^l = 10$ multi-paths. A control cognitive radio channel, with a TDMA or a FDMA, is as well used by the FC and the CRs. We define $D_f = \Delta f_{opt}/\Delta f'$ as the sensing frequency precision where $\Delta f_{opt} = \min\left(\Delta f_{\min}, B_{\min}\right)$. $\Delta\varepsilon = \left(\varepsilon_{k'}^H - \varepsilon_{k'}^L\right)/\left(2\varepsilon_{k'}\right)$ allows to change the double threshold width. T_c is set to 1 *ms* and we suppose a low spectrum sensing time while fixing α = 90%.

Fig. 6 shows the SSB width impact on the probability of detection. We see that our system is able to maintain a cooperative detection probability of 0.9, with a loss of detectable PU SNR of 2.5dB ($D_f = 0.78$) and 4dB ($D_f = 0.70$) when compare with the optimal case ($D_f = 1$). Note that, the method proposed in [11] is

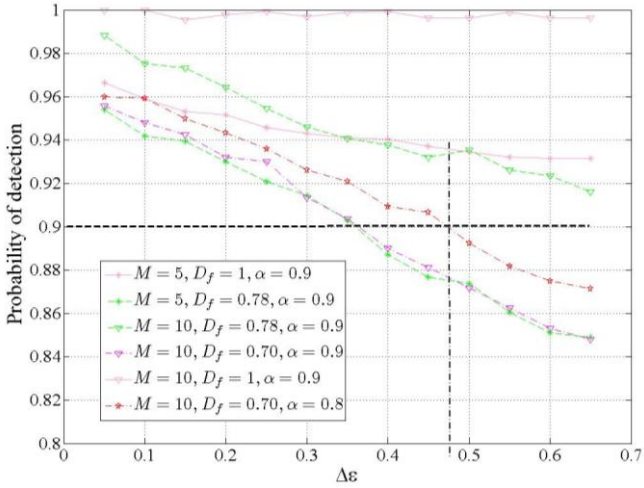

Figure 8 – Probability of detection versus $\Delta\varepsilon$ ($Q_{fa} = 0.05$, SNR = 0dB)

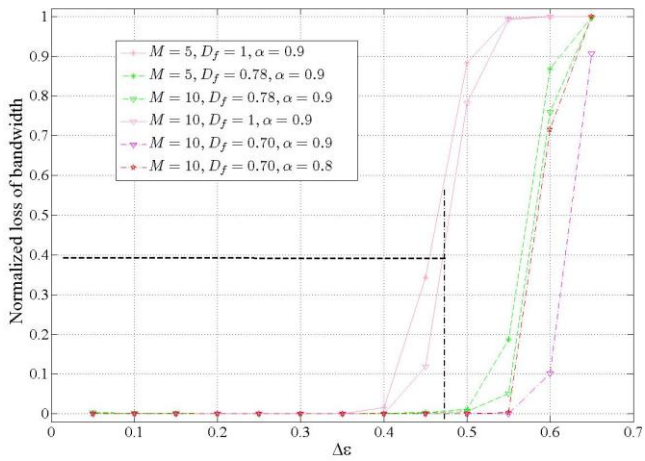

Figure 9 – Normalized loss of bandwidth versus $\Delta\varepsilon$ ($Q_{fa} = 0.05$, SNR = 0dB)

equivalent to considering $D_f << 1$ and so we can see that, contrary to our method, many free bands are undetected.

When the targeted probability of detection is reached, Fig. 7 shows that there is no loss of available bandwidth when $D_f = 0.78$, whereas, when $D_f = 0.70$, the normalized loss of bandwidth is of 2.10^{-3}, which corresponds to 200kHz.

Fig. 8 and 9 show the $\Delta\varepsilon$ influences on the probability of detection for various M, α and D_f, when SNR = 0dB. On Fig. 8, we see that if we decrease the spectrum sensing time efficiency ($\alpha = 0.8$), we can maintain $Q_d = 0.9$, until $\Delta\varepsilon = 0.48$ when $M = 10$ and $D_f = 0.70$ with $\Delta W_k = 0$ (see Fig. 9). According to [14] the higher $\Delta\varepsilon$, the higher efficient the spectrum sensing in term of bandwidth constraints. Thus, considering $\Delta\varepsilon = 0.48$, in Fig. 9, we see that if we consider the optimal case (i.e. $D_f = 1$, $\alpha = 0.9$ and $M = 10$ for which Q_d is maximal $\forall\Delta\varepsilon$), we have $\Delta W_k = 0.38$. So, we can conclude that the better solution according to (20) is for $\alpha = 0.8$ and $D_f = 0.70$.

5. CONCLUSION

The proposed CRN is coherent with CR concept introduced by J. Mitola. Indeed, it can quickly detect in a cooperative way PUs in a wideband spectrum, while maintaining a high Q_d. Furthermore, we propose a distributed wideband spectrum sensing CRN, which makes it possible to have an optimal spectrum sensing time and to detect narrow-band PU signals.

In fact, it may be that SB division was not narrow enough, therefore leading to a huge loss of available bandwidth. The proposed structure can adapt to the detection of PU signals, and have a high detection probability with a weak loss of available bandwidth when a narrowband PU exists in the analyzed SB. To our knowledge, this kind of system has never been addressed in the open literature. Moreover, the distributed spectrum sensing between SCRN that we propose, enables to reduce the energy spent by individual CR to perform the detection. Finally, we have considered a wideband spectrum division, which does not cut occupied bands. But, in practice, this hypothesis cannot be sure. In future studies, in order to take a more realist vision into account, a sliding WSS division could be considered.

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