An Area And Power Efficient Two-Stage Parallel Spectrum Sensing Scheme For Cognitive Radios

S. J. Darak and A. P. Vinod
School of Computer Engineering
Nanyang Technological University, Singapore
{dara0003, asvinod}@ntu.edu.sg

E. M-K. Lai
School of Engineering and Advanced Technology
Massey University, Albany, New Zealand
E.Lai@massey.ac.nz

***Abstract*— In this paper, an area and power efficient two-stage spectrum sensing scheme for cognitive radios (CRs) is proposed. A typical parallel spectrum sensing using filter bank has advantages of lowest mean detection time, less interference to primary users and better throughput over serial spectrum sensing. However, these advantages come at the huge cost of increased area complexity and power consumption. The two-stage spectrum sensing consists of basic sensing stage using energy detection (ED) followed by advanced sensing stage using cyclostationary feature detection (CFD). The computation complexity and power consumption of CFD is very high compared to ED. Based on several spectrum occupancy measurement surveys conducted worldwide, we conclude that not all the CFD blocks in a typical parallel sensing scheme are fully utilized due to relatively sparse spectrum. Motivated by this observation, we propose a spectrum sensing scheme with reduced number of CFD blocks optimized based on spectrum occupancy information. The proposed scheme offers substantial reductions in area and power consumption while achieving same performance in terms of mean detection time compared with other existing spectrum sensing schemes.**

I. INTRODUCTION

Cognitive radio (CR) has been proposed as an efficient solution for mitigating the imbalance between the spectrum scarcity because of the remarkable growth of new wireless services and poor spectrum utilization mainly due to spectrum management policies [1, 2]. In CR network, the secondary user (unlicensed user) scans the licensed spectrum possibly several hundreds of MHz to search for vacant band (this process is called as spectrum sensing) and ensure adaptive transmission within vacant band without causing interference to primary user (licensed user) who have higher priority [3]. The secondary users need to scan the spectrum in scenarios such as: 1) Start new data transmission, 2) Switch to other frequency band when primary user arrives, 3) Find a vacant band with more bandwidth, desired frequency range or less interference to improve the performance. The CRs finds application in smart grid networks, public safety networks, wireless medical networks, cellular networks etc [4]. For critical applications like public safety, wireless medical or cellular networks, CRs are constrained to quickly search single vacant band and start transmission. Hence, the reliable, fast spectrum sensing with low implementation complexity is the most important attribute of CR.

There are a number of spectrum sensing techniques such as energy based detection (ED), matched filter (MF) detection, cyclostationary feature based detection (CFD), Eigen value based detection (EVD) etc proposed and theoretically analyzed in the literature [5-10]. The MF detector and ED represent two ends of the traditional spectrum sensing detectors design space. The MF is an optimum signal detector since it maximizes received signal-to-noise (SNR) ratio and it needs fewer samples to meet a given probability of detection. However, MF requires priory information about primary user such as modulation type, order etc and employs dedicated receiver for each primary user. Hence, it is not suitable for CR environment. ED is simple, easy to implement if the noise power at the receiver is known and has short detection time. But it has high probability of false alarm at low SNR, performs poorly in shadowing/fading environments and is vulnerable to uncertainty in noise power. The CFD takes advantage of the cyclostationary properties of modulated signals to decide whether primary user is present or not. CFD has better performance and huge processing gain over ED and EVD when the SNR is low. However, this advantage comes at the expense of a significant computational complexity and longer mean detection time than ED. Hence, all these techniques fall short of the performance and complexity requirements of a spectrum sensing in CR.

The new two-stage spectrum sensing approaches proposed in [6-10] consist of two stages namely basic sensing and advanced sensing (termed coarse sensing and fine sensing in literature). The main function of the basic sensing stage is to detect strong primary/secondary users quickly and ED is generally preferred choice for basic sensing stage due to its advantages discussed before [6-10]. The advanced sensing stage is activated only if ED decides signal is absent and SNR is below critical SNR [9]. It is done either using ED but with smaller subband bandwidth than basic sensing [6] or CFD [7-9] or EVD [10]. The two-stage spectrum sensing provides improved detection performance than single stage ED and lower mean detection time compared to single stage CFD [7-9].

In two-stage spectrum sensing, wideband input signal is sensed either serially using filter or in parallel using filter bank. The serial spectrum sensing is an area and power efficient since it requires only one ED and CFD. However, mean detection time in serial spectrum sensing is very high given that one band is sensed at a time and it degrades when the number of active primary users' increases. The higher mean detection time leads to high interference with primary users. Also, it reduces the time available for useful communication, which in turn reduces the achievable throughput. To achieve lowest mean detection time (i.e. time taken by ED and CFD together), parallel sensing using filter bank is the suitable option where each subband of filter bank is sensed simultaneously using dedicated sets of ED and CFD block. Furthermore, when information about multiple vacant bands are available, it is desirable to select the widest subband or fuse multiple contiguous narrow sub-bands to obtain a wider bandwidth. A wider vacant subband offers more protection against flat fading and greater opportunities for frequency diversity schemes which can offer protection against frequency selective fading [11]. However, the area complexity and power consumption increases linearly with the number of ED and CFD blocks.

In this paper, we focus on an area and power efficient two-stage filter bank based spectrum sensing using ED and CFD for applications such as public safety, wireless medical or cellular networks. For example, wireless devices used in public safety networks are required to quickly search and access single vacant band to prevent or respond to emergency events instead of searching all the vacant bands. Also, area and power consumption of wireless devices must be low to make it handy to use and lasts for a longer duration in emergency situations. We analyzed the surveys conducted by various countries which indicated that around 10-60% of the spectrum is underutilized [1, 12-14] and spectrum utilization does not vary radically in a specified region. This observation leads us to the conclusion that not all the CFD blocks in a parallel ED-CFD sensing scheme need to be fully utilized. Based on this observation, we propose a low complexity implementation of two-stage spectrum sensing by reducing the number of CFD blocks. The mean detection time to search a single vacant band of the proposed scheme is equal to that of the parallel sensing scheme.

The paper is organized as follows. The proposed spectrum sensing scheme is presented in Section II. In Section III, the relation between mean detection time, spectrum occupancy and number of CFDs is derived. The implementation results and complexity comparison with parallel sensing are presented in Section IV. Section VI concludes the paper.

II. TWO-STAGE PARALLEL SPECTRUM SENSING

The proposed spectrum sensing scheme, as shown in Fig. 1, consists of a N subband filter bank followed by N EDs and M ($\leq N$) CFDs. When the wideband input signal is divided into N subbands using filter bank, the M_{ed} samples of the received signal $x_i[n]$, i=1, 2, ...N and n= 1, 2, ...M_{ed} in the i^{th} sub-band can be described as

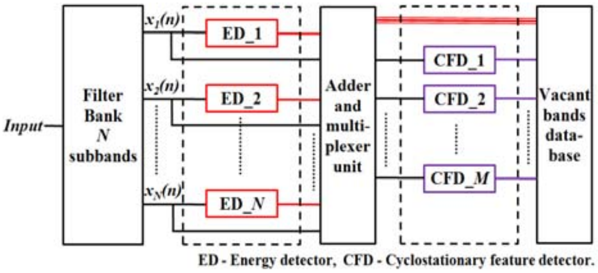

Fig. 1. Proposed spectrum sensing scheme.

$$x_i[n] = w_i[n] + s_i[n] \quad \text{in Primary/secondary user presence} \quad (1)$$
$$x_i[n] = w_i[n] \quad \text{in Primary/secondary user absence}$$

where $w_i[n]$ is an addictive white Gaussian noise (AWGN) with statistics $\square(0,\sigma_\omega^2)$ and $s_i[n]$ is a primary/secondary signal in the i^{th} sub-band with statistics $\square(0,\sigma_s^2)$. The i^{th} ED block, ED_i, collects the energy of M_{ed} samples of $x_i[n]$ and compares it with a threshold λ to decide whether subband is free or not. The test statistic, Z_i, for i^{th} subband is given by,

$$Z_i = \sum_{n=1}^{M_{ed}} x_i[n]^2, \quad i = 1,2,.....N. \quad (2)$$

If Z_i is greater than λ, then ED_i will report i^{th} subband as occupied. If Z_i is smaller than λ, then ED_i will report i^{th} sub-band as free. The adder and multiplexer unit selects M of these free subbands for advanced sensing and pass M_{cfd} samples of each M subbands to CFD blocks. The subbands reported as free by CFD could be used by secondary users. Since the proposed scheme and those in [7-9] use ED and CFD, their performance in terms of probability of false alarm and probability of detection at different SNRs can be assumed to be identical. Hence, the mathematical equations and analysis of the ED and CFD performance are not discussed in detail here.

The computational complexity and mean detection time of spectrum sensing is also a great concern for CR other than detection performance. The number of real multiplications and additions for CFD are ($32M_{cfd}^2$ +$24M_{cfd}$ +4) and ($32M_{cfd}^2$

+16M_{cfd} -2) respectively compared to (4M_{ed}) and 2(2M_{ed} -1) respectively for ED [15]. For example, when $M_{ed} = M_{cfd} = 50$, the number of real multiplications and additions in CFD are 81204 and 80798 respectively compared to 200 and 198 for ED. Thus, complexity of two-stage spectrum sensing is dominated by CFDs. By taking into account the complexity concerns for real-time implementation of the CFD, alternative solutions such as single-peak, twin-peak detectors, pilot assisted cyclostationary detection (PACD) have been presented in [9, 15]. Though these methods considerably reduce the computational burden, the number of multipliers and adders are still 3 to 8 times compared to ED. On the other hand, complexity reduction results in degradation of detection performance or longer mean detection time. The spectrum sensing schemes in [8, 9] provide solutions to significantly reduce the dynamic power consumption when SNR is high. In both approaches, SNR information is used to decrease the dynamic power consumption by reducing the number of activation of advanced sensing stage but area complexity and static power consumption remains the same.

III. MEAN DETECTION TIME, SEPCTRUM OCCUPANCY AND NUMBER OF CYCLOSTATIONARY FEATURE DETECTORS

We studied spectrum occupancy measurement campaigns conducted over longer time periods in Chicago (2 days) [12], Germany (7 days) [13] and Singapore (12 days) [14] etc. Several such studies are being conducted all around the world. These details and long term measurements reveal that the spectrum occupancy varies from 10% to 60% depending on bandwidth under consideration in a given region. In addition, they provide valuable information about the primary users' activity, projected spectrum usage pattern, interference and noise level. Many of the today's spectrums sensing schemes make use of this information to improve performance parameters such as probability of detection, mean detection time etc. The proposed scheme reduces the complexity of conventional two-stage spectrum sensing using the available spectrum occupancy information.

Consider the scenario where CRs are allowed to use vacant frequency bands anywhere in relatively wide bandwidth B. Assume that the spectrum occupancy measurements are conducted beforehand and maximum spectrum occupancy over bandwidth B due to active primary users is observed as s%. When the bandwidth B is divided into N subbands using filter bank, the number of free subbands, N_{free}, is equal to or greater than (3).

$$Nfree \geq \left\lfloor \left(1 - \frac{s}{100}\right) N \right\rfloor . \tag{3}$$

The significance of N_{free} is that it tells us about the minimum value of M (number of CFD blocks) to achieve lowest mean detection time. We assume that the secondary users are able to control their transmitted signals such that they can be easily detected in basic sensing stage. This will help secondary users to efficiently use sensing time and valuable resources such as CFDs for weak primary users detection.

The mean detection time $(T_{mean})_{M,s}$ to find first vacant band depends on spectrum occupancy (s%), number of CFDs (M), number of subbands or EDs (N), detection time of ED (T_{ed}) and CFD (T_{cfd}), and is given by (4). The problem is to find the range of values of M for a given s that will result in lowest $(T_{mean})_{M,s}$ which is equal (T_{ed} + T_{cfd}). Using (3) & (4), the lower and upper bound on M which will result in lowest $(T_{mean})_{M,s}$ are obtained as (N-N_{free}+1) and N respectively.

$$(T_{mean})_{M,s} = T_d \left\{ \begin{array}{l} \left[1 - \left(\dfrac{{}^{L}C_M}{{}^{N}C_M} . ge(L,M) \right) \right] + \\ \displaystyle\sum_{i=1}^{\left\lfloor \frac{L}{M} \right\rfloor} \left[\begin{array}{l} (i+1)\left(1 - \left(\dfrac{{}^{L-iM}C_M}{{}^{N-iM}C_M} . ge(L-iM,M) \right)\right) \\ \left(\displaystyle\prod_{k=0}^{i-1} \dfrac{{}^{L-kM}C_M}{{}^{N-kM}C_M} \right) \end{array} \right] \end{array} \right\} \tag{4}$$

where,

$$T_d = (T_{ed} + T_{cfd}).$$

$$L = N - N_{free}$$

$${}^{n}C_k = \frac{n!}{(n-k)!k!}.$$

$$ge(x,y) = 1 \quad x \geq y.$$
$$ = 0 \quad x < y.$$

In Fig. 2, the relationship between $(T_{mean})_{M,s}$, number of CFDs i.e. M for different spectrum occupancy (s%) is plotted. It can be observed that serial sensing fails to achieve lowest $(T_{mean})_{M,s}$ except when N=N_{free} i.e. all sub-bands are free whereas $(T_{mean})_{M,s}$ for parallel sensing is always lowest i.e. (T_{ed} + T_{cfd}). The proposed sensing scheme with N EDs and M (=N-N_{free}+1) CFDs achieves lowest $(T_{mean})_{M,s}$ for all s. The mean detection time to find remaining vacant bands, $(T_{all\_mean})_M$ is inversely proportional to number of CFDs (M). Hence, higher M will result in an early knowledge about other vacant subbands which will help the secondary users to select the most favorable vacant subband. However, higher the value of M (i.e. number of CFDs), higher the computational complexity and power consumption will be. The total saving achieved using the proposed scheme is dependent on s and discussed in Section IV.

IV. IMPLEMENTATION COMPLEXITY

In this section, comparison of the serial, parallel and proposed spectrum sensing schemes with respect to parameters such as number of slices, multipliers, mean detection time, static and dynamic power consumption is presented. The frequency band from 1710 MHz to 1880 MHz, with spectrum occupancy (s) of 36% [14], is considered for spectrum sensing. The wideband input signal

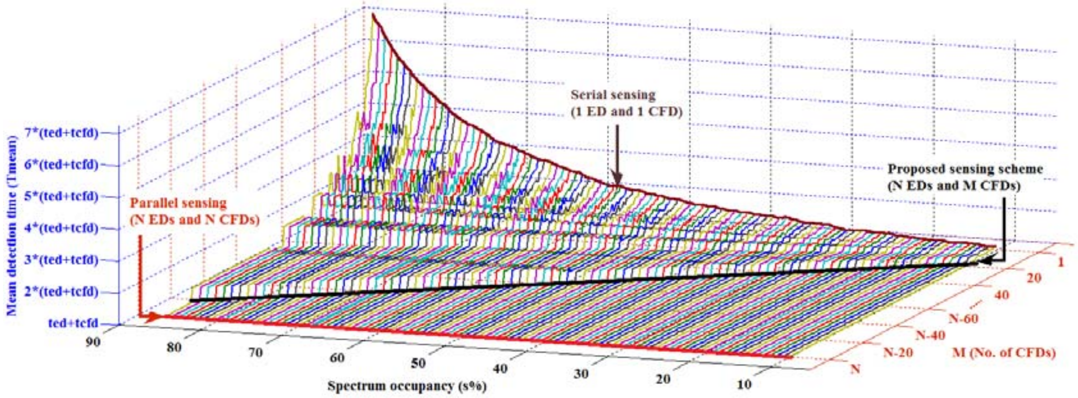

Fig. 2. Relation between mean detection time (T_{mean}), spectrum occupancy (s%) and M (No. of CFDs).

is divided into 16 subbands each of bandwidth 10.625 MHz. The number of EDs (N) is 16. The number of CFDs (M) for the proposed scheme, obtained using (3) & (4), are 7 compared to 16 for parallel sensing. All the other parameters such as SNR, probability of false alarm, probability of detection are same for both the schemes.

We have used the implementation results of ED and CFD blocks on Xilinx Virtex xc4vsx35-10ff668 FPGA presented in [9]. The bit stream is generated using a Xilinx system generator. The power consumption figures were calculated using X-power. The area results are obtained using log viewer block provided by Lyrtech [16]. The implementation results for s=36% are summarized in Table I. The mean detection time is obtained using (3) and (4) where T_{ed}= 20ms and T_{cfd}=180ms [9]. The values "±x%" in last column of Table I indicate the percentage savings in respective parameters when compared with the parallel sensing. It can be observed that the proposed sensing scheme offers substantial reductions in area and power consumption over parallel sensing scheme. Though the serial spectrum sensing, which consists of 1 ED and 1 CFD, has lower implementation complexity and static power consumption, the mean detection time of serial sensing is very high compared to proposed sensing. The lower mean detection time leads to more time for data transmission for secondary users and hence higher spectrum utilization efficiency.

The percentage saving shown in Table I depends on spectrum occupancy (s%) which varies from one geographical region to another. The relationship between spectrum occupancy (s%) and percentage savings is shown in Fig. 3. It can be observed that the proposed scheme offers substantial savings in number of slices, multipliers, static and dynamic power consumption especially when spectrum is relatively sparse.

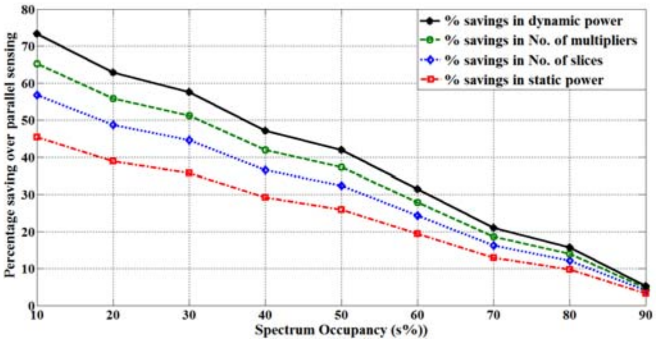

Fig. 3. Spectrum occupancy (s%) vs. percentage savings achieved using proposed method over parallel sensing scheme.

V. CONCLUSION

In this paper, an area and power efficient two-stage spectrum sensing scheme for cognitive radios (CRs) is proposed. The proposed spectrum sensing scheme consists of a N subband filter bank followed by N energy detectors and M ($\leq N$) cyclostationary feature detectors. We obtained the optimum value of M that will result in lowest mean detection

TABLE I. IMPLEMENTATION COMPLEXITY COMPARISON

Sensing schemes	**Parallel Sensing (16 ED and 16 CFD) [9]**	**Serial Sensing (1 ED and 1 CFD) [7]**	**Proposed Sensing (16 ED and 7 CFD)**
No. of Slices	97984	6124 **(-93.75%)**	62254 **(-36.5%)**
No. of multipliers	816	51 **(-93.75%)**	474 **(-41.9%)**
Static power (W)	14.77	0.922 **(-93.75%)**	10.45 **(-29.2%)**
Dynamic power (W)	17.5	17.5 **(0%)**	9.253 **(-47%)**
$(T_{mean})_{M,s}$ (ms)	200	309 **(+154.6%)**	200 **(0%)**
$(T_{all\_mean})_M$ (ms)	200	3090	575

time for a given spectrum occupancy (s%). The implementation results showed that the proposed scheme offers substantial savings over parallel sensing scheme in number of slices, multipliers, static and dynamic power consumption especially when spectrum is relatively sparse. The future work will focus on optimizing the filter bank and energy detection stage which will further reduce the computational load on cyclostationary feature detectors.

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