

# Signal Assemblage Based Wideband Spectrum Sensing for OFDM Cognitive Radios

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**Abstract**—This paper investigates power-law detector (PLD) based wideband spectrum sensing schemes for OFDM cognitive radios. By exploiting signal assemblage (SA) feature of the primary user (PU), we first propose a heuristic iterative threshold test (HITT) to roughly detect the SA set boundary of the noise and PU signal; Subsequently, a signal assemblage cardinality measuring (SACM) method is developed to refine the HITT decisions. Operating in SA-based wideband sensing manner, the PLD greatly overcomes the ambiguity in differentiating weak PU subcarriers from noise and significantly meliorates the sensing performance, compared with the non-SA methods.

**Index Terms**—Power-law detector, signal assemblage, cognitive radio, energy detector.

## I. INTRODUCTION

With an opportunistic mechanism of accessing the licensed spectrum temporarily unoccupied by the primary users (PUs), cognitive radio (CR) is commonly considered as one of the key technologies to solve the spectrum scarcity problem aroused by the ever-increasing spectrum demand for the emerging wireless service and applications nowadays. Among the various spectrum cognition solutions, wideband spectrum sensing has attracted wide attentions, owing to its capability of identifying the the PU signal's whereabouts within the wideband licensed spectrum of interest. Through wideband spectrum sensing, the secondary users (SUs) are able to pinpoint the white frequency bins that could be dynamically utilized in different ways.

In order to identify spectrum opportunities for CRs, power-law detector (PLD), energy detector (ED), and eigenvalue-based detector (EBD) in narrowband signal detection applications [1] [2] [3] [4] [5] [6] [7] are widely adopted for narrowband spectrum sensing, owing to its simple circuitry. Generally, the wideband spectrum sensing strategies can be categorized into unchannelized and channelized ones. The unchannelized wideband sensing methods obtain the decision of the whole wideband licensed spectrum directly, whereas regarding that identifying the white subcarriers for secondary access is of the highest priority, the channelized wideband sensing algorithms first partition the whole spectrum into multiple subcarriers [8] with quite much narrower bandwidth and then decisions on the individual status of them are acquired simultaneously.

Problems of unchannelized wideband sensing methods can be easily seen in some aspects. If by nature the PU signal only resides in a small portion of the wideband licensed spectrum, the sensing decision will be vulnerable to the cumulative noise effect within the wideband spectrum and meanwhile the intrinsically low spectrum resolution of unchannelized methods would result in a waste of the unused spectrum for the CR systems. For a cognitive OFDM system, the licensed wideband is resolved into a series of contiguous subcarriers, where the task of wideband spectrum sensing is to categorize the subcarriers into a set of PU occupied subcarriers and a set of idle ones, through individual subcarrier test or multi-subcarrier joint test [9] [14].

In [9], the problem of multiband joint detection was solved by maximizing the aggregated opportunistic throughput of a CR system under given interference constraints. In [10], wideband sensing is tackled under the framework of information-theoretic signal processing criteria, where conventional source number estimation strategies, algorithms were adopted for extracting the PU-occupied subcarriers. After that, the information theory criterion based wideband spectrum sensing is still attracting research efforts [11] [12]. In [14], maximum likelihood estimates was employed in wideband sensing to gather information of the PU's whereabouts and subsequently the single band detection was performed to obtain the final decisions.

Aiming to circumvent the requirement of *a priori* knowledge of the noise power and the PU signals in [9] [14], we investigate signal assemblage (SA) based wideband sensing in an entirely new mechanism. We first propose a heuristic iterative threshold test (HITT) algorithm to coarsely determine the SA set boundary of the noises and the PU signals, without demanding any readily available knowledge of the PU systems and the noise. Subsequently, we develop a refining method to meliorate the HITT performance, further aided by the intrinsically salient assemblage properties of PU signals.

Computer simulations are carried out to evaluate the wideband sensing performance of the proposed algorithms. As expected, the HITT algorithm is able to achieve a detection rate quite close to that of the ISTT algorithm for which *a priori* knowledge of the noise power is readily known at the receiver. As for the SACM algorithms, wideband sensing performance enhancement is easy to be found when the signal-to-noise ratio is getting large enough. Furthermore, it is worth mentioning

that as basically the constant false alarm rate (CFAR) criterion based wideband sensing algorithms, the proposed methods all strictly guarantee that the false alarm rates are less than the desired one.

The rest of this paper is organized as follow: system model is introduced in Section II. Section III presents the signal assemblage based wideband sensing schemes. Simulation result is presents in Section IV. Section V is the conclusion.

## II. SYSTEM MODEL

Suppose there are  $M$  independent PU systems orthogonally operating in the licensed wideband, with the  $m$ th PU ( $1 \leq m \leq M$ ) occupying the band from the  $q_{m,0}$ th to the  $q_{m,1}$ th subcarriers of the cognitive OFDM system.

The received signal is passed through a  $Q$ -point discrete Fourier transform (DFT) and, for subcarrier  $q$ , the DFT output of the  $k$ th time segment is:

$$Y_q(k) = \begin{cases} I_q(k) + V_q(k) & \mathcal{H}_{q,1}, \quad k \in \{0, 1, \dots, K-1\}, \\ V_q(k) & \mathcal{H}_{q,0}, \quad q \in \{1, 2, \dots, Q\} \end{cases} \quad (1)$$

where  $I_q(k) \sim \mathcal{CN}(0, \sigma_q^2)$  is the PU signal,  $V_q(k) \sim \mathcal{CN}(0, \sigma_0^2)$  the white Gaussian noise, and  $K$  the number of DFT operations per sensing interval.

Utilizing PLD, we obtain the  $q$ th power samples as  $X_q(k) = |Y_q(k)|^2$ . According to Nuttall's theorem [1], the probability density functions<sup>1</sup> (PDF) of  $\mathbf{X}(k) = [X_1(k), X_2(k), \dots, X_Q(k)]^T$  under hypotheses  $\mathcal{H}_0$  and  $\mathcal{H}_1$  are respectively:

$$f_0(\mathbf{X}(k)|\mathcal{H}_0) = \prod_{q=1}^Q \frac{1}{\sigma_0^2} \exp\left(-\frac{X_q(k)}{\sigma_0^2}\right) u(X_q(k)), \quad (2)$$

$$f_1(\mathbf{X}(k)|\mathcal{H}_1) = \prod_{q \in \mathbb{S}_0} \frac{1}{\sigma_0^2} \exp\left(-\frac{X_q(k)}{\sigma_0^2}\right) u(X_q(k)) \times \prod_{m=1}^M \left[ \prod_{q \in \mathbb{S}_m} \frac{1}{\sigma_0^2 + \sigma_q^2} \exp\left(-\frac{X_q(k)}{\sigma_0^2 + \sigma_q^2}\right) u(X_q(k)) \right], \quad (3)$$

where  $\mathbb{S}_{\text{PU}} \triangleq \bigcup_{m=1}^M \mathbb{S}_m$  with  $\mathbb{S}_m = \{q_{m,0}, q_{m,0} + 1, \dots, q_{m,1} - 1, q_{m,1}\}$ , containing all indices of the PU-occupied subcarriers;  $\mathbb{S}_0 = \overline{\mathbb{S}_{\text{PU}}}$  is the index set of idle subcarriers; and  $u(\cdot)$  is the unit step function.

The conventional individual subcarrier threshold test (ISTT) for the  $q$ th subcarrier,  $q \in \{1, 2, \dots, Q\}$ , is:

$$Z_q = \sum_{k=0}^{K-1} X_q(k) \geq \lambda_{\text{ISTT}} \Rightarrow \begin{cases} \text{true}, & q \in \hat{\mathbb{S}}_{\text{PU}} = \bigcup_{m=1}^{M'} \hat{\mathbb{S}}_m, \\ \text{false}, & q \in \hat{\mathbb{S}}_0 = \overline{\hat{\mathbb{S}}_{\text{PU}}}, \end{cases} \quad (4)$$

where  $\lambda_{\text{ISTT}}$  is the ISTT threshold,  $\hat{\mathbb{S}}_m = \{d_{m,0}, d_{m,0} + 1, \dots, d_{m,1} - 1, d_{m,1}\}$  the  $m$ th index set of the detected PU-subcarriers,  $\hat{\mathbb{S}}_0$  the index set of the decided noise-only

<sup>1</sup>The precise PDF under  $\mathcal{H}_1$  strictly depends on the  $M$  PUs' signal structures and we have no particular reason to take (3) as fact. Nevertheless, there is considerable flexibility and convenience in using (3) for signal modeling (mostly through the unspecified  $\{\mathbb{S}_m\}_{m=1}^M$ ).

subcarriers, and  $M'$  the number of detected PU systems.

Based on  $\hat{\mathbb{S}}_{\text{PU}}$ ,  $\hat{\mathbb{S}}_0$ , and  $\mathbb{S}_{\text{PU}}$ , the wideband sensing performance is:

$$R_D = \frac{\mathcal{R}[\hat{\mathbb{S}}_{\text{PU}} \cap \mathbb{S}_{\text{PU}}]}{\mathcal{R}[\mathbb{S}_{\text{PU}}]}, \quad (5)$$

$$R_{\text{FA}} = P(\mathcal{H}_0) \times \frac{\mathcal{R}[\hat{\mathbb{S}}_{\text{PU}}]}{Q} + P(\mathcal{H}_1) \times \frac{\mathcal{R}[\hat{\mathbb{S}}_0 \cup \overline{\mathbb{S}}_{\text{PU}}]}{Q - \mathcal{R}[\mathbb{S}_{\text{PU}}]},$$

where  $\mathcal{R}[\cdot]$  gives the cardinality of a set,  $R_D$  is the detection rate,  $R_{\text{FA}}$  is the false alarm rate,  $P(\mathcal{H}_0)$  and  $P(\mathcal{H}_1)$  are the probabilities of PU signals being absent and active, respectively.

## III. SIGNAL ASSEMBLAGE BASED WIDEBAND SENSING SCHEMES

The PU's SA feature is a generic characteristic that may, in some extent, offer detection robustness against the dynamically varying channel effects. Particularly, it lies in two aspects: One is the ensemble average signal strength (EASS) difference between  $\mathbb{S}_0$  and  $\mathbb{S}_{\text{PU}}$ ; the other one is the PU-present subcarriers' congregativeness in  $\mathbb{S}_{\text{PU}}$ , where the PU signals usually reside in some spectrum segments, with PU-occupied subcarriers consecutively agglomerating in each segment.

### A. Signal Assemblage Set Boundary Test

Based on  $\mathbf{Z} = [Z_1, Z_2, \dots, Z_Q]^T$ , we develop the HITT algorithm to decide the SA set boundary between  $\mathbb{S}_0$  and  $\mathbb{S}_{\text{PU}}$  via EASS comparisons. In general, the EASS of  $\mathbb{S}_0$  is always less than that of  $\mathbb{S}_{\text{PU}}$ . Given an initial index set of some smallest noise-only observations from  $\mathbf{Z}$ , i.e.  $\mathbb{S}_{0,1}$ , we can increase its cardinality by iteratively adding the rest larger observations as its new elements to obtain a series of pre-assumed noise-only subcarrier sets  $\mathbb{S}_{0,i}$ ,  $i \geq 1$ . If the EASS of  $\mathbb{S}_{0,i}$  is less than the newly added observation, the SA set boundary is found.

By assuming there is always at least  $L$  noise-only subcarriers in the wideband ( $L/Q \ll 1$ ), we carry out the HITT algorithm as follows:

**Step 1)** The observations  $\mathbf{Z} = [Z_1, Z_2, \dots, Z_Q]^T$  are sorted as  $\tilde{\mathbf{Z}}$  in an ascending order with  $\tilde{\mathbf{Z}} = [\tilde{Z}_1, \tilde{Z}_2, \dots, \tilde{Z}_Q]^T = [Z_{1'}, Z_{2'}, \dots, Z_{Q'}]^T$ , where  $\tilde{Z}_1 \leq \tilde{Z}_2 \leq \dots \leq \tilde{Z}_Q$  and  $\{1', 2', \dots, Q'\}$  is a permutation of  $\{1, 2, \dots, Q\}$ .

**Step 2)** The first  $L$  smallest elements  $\{\tilde{Z}_l\}_{l=1}^L$  are assumed to contain noise only and their indices form the initial set  $\mathbb{S}_{0,1} = \{1, 2, \dots, L\}$ , on which the iterative EASS comparison begins from  $i = 1$ :

$$\rho_i = \frac{1}{i} \sum_{l=1}^{L+i-1} \tilde{Z}_l \cdot \lambda_{\text{HITT}} \geq \tilde{Z}_{L+i} \quad (6)$$

$$\Rightarrow \begin{cases} \text{true, the index of } \tilde{Z}_{L+i} \in \mathbb{S}_{0,i}, \\ \text{false, SA set boundary } B \text{ is found,} \end{cases}$$

where  $\rho_i$  is the EASS of  $\mathbb{S}_{0,i}$  in the  $i$ th iteration and  $\lambda_{\text{HITT}}$  is the threshold.

**Step 3)** If the first HITT test ( $i = 1$ ) of (6) is *false*, the algorithm stops. We decide the SA boundary as  $B = L$  and

obtain  $\hat{\mathbb{S}}_0 = \mathbb{S}_{0,1} = \{1, 2, \dots, B\}$  and  $\hat{\mathbb{S}}_{PU} = \{d_j = B+j|B = L, j = 1, 2, \dots, Q-B\}$  with  $\mathcal{R}[\hat{\mathbb{S}}_{PU}] = Q-B$ ; otherwise, the test in (6) is performed again with  $i$  incremented by 1.

**Step 4)** The iterative test in (6) is repeated till it is *false* for  $i = \xi$ . The SA set boundary is obtained as  $B = L + \xi - 1$ . Correspondingly, we have  $\hat{\mathbb{S}}_0 = \mathbb{S}_{0,\xi} = \{d_j = j|j = 1, 2, \dots, B\}$  and  $\hat{\mathbb{S}}_{PU} = \{d_j = B+j|B = L+\xi-1, j = 1, 2, \dots, Q-B\}$ . Note that a special case occurs if (6) is always *true* till  $i = Q-L$ , implying that the boundary  $B$  does not exist after thorough EASS comparisons over  $\tilde{\mathbf{Z}}$ . Hence, we have  $\hat{\mathbb{S}}_0 = \mathbb{S}_{0,Q-L}$  and  $\hat{\mathbb{S}}_{PU} = \emptyset$ .

**Step 5)** Based on  $\hat{\mathbb{S}}_{PU}$ , the original indices of the PU subcarriers  $\{(B+1)', (B+2)', \dots, Q'\}$  are very easy to find.

The complementary cumulative distribution function of  $\tilde{Z}_i$  under  $\mathcal{H}_0$  is [2]

$$F_c(\tilde{Z}_i|\mathcal{H}_0) = \exp\left(-\frac{\tilde{Z}_i}{2\sigma_0^2}\right) \sum_{k=0}^{K-1} \frac{1}{k!} \left(\frac{\tilde{Z}_i}{2\sigma_0^2}\right)^k u(\tilde{Z}_i), \quad (7)$$

and given a desired probability of false alarm  $P_{FA,DES}$ , we reach the theoretical  $\lambda_{ISTT}$  by solving  $P_{FA,DES} = \text{Prob}\{\tilde{Z}_i > \lambda_{ISTT}|\mathcal{H}_0\} = F_c(\lambda_{ISTT}|\mathcal{H}_0)$ .

As for the theoretical  $\lambda_{HITT}$ , we can obtain it by solving

$$\begin{aligned} \text{Prob}\{\tilde{Z}_{i+1} > \rho_i|\mathcal{H}_0\} &\approx \text{Prob}\{\tilde{Z}_{i+1} > \sigma_0^2 \cdot \lambda_{HITT}|\mathcal{H}_0\} \\ &= \exp\left(-\frac{\lambda_{HITT}}{2}\right) \sum_{k=0}^{K-1} \frac{1}{k!} \left(\frac{\lambda_{HITT}}{2}\right)^k \\ &= P_{FA,DES}, \end{aligned} \quad (8)$$

where the approximation is based on the fact that the EASS  $\rho_i$  is estimated by the ensemble mean of the  $L+i$  observations in the  $i$ th iteration of (6). It is specially worth noting that  $\lambda_{HITT}$  is independent of  $\sigma_0^2$ .

### B. Signal Assemblage Subset Cardinality Measuring

The HITT is essentially a coarse wideband sensing method. Statistically, some noise-only subcarriers may exhibit larger strength than the EASS of  $\mathbb{S}_{0,i}$ , whereas some considerably attenuated PU-occupied subcarriers may behave like noise-only ones. We further develop a method of SA cardinality measuring (SACM) to enhance the HITT (or ISTT) as follows: **Step 1)** The HITT (or ISTT) algorithm is independently executed twice by using  $\lambda_U$  and  $\lambda_L$ , ending up with decision sets  $\hat{\mathbb{S}}_{PU,U}$  and  $\hat{\mathbb{S}}_{PU,L}$  respectively.

**Step 2)** We divide  $\hat{\mathbb{S}}_{PU,U}$  and  $\hat{\mathbb{S}}_{PU,L}$  into multiple subsets:

$$\hat{\mathbb{S}}_{PU,U} = \bigcup_{m=1}^{M'} \hat{\mathbb{S}}_{U,m}, \quad \mathcal{R}[\hat{\mathbb{S}}_{PU,U}] = \sum_{m=1}^{M'} \mathcal{R}[\hat{\mathbb{S}}_{U,m}], \quad (9)$$

$$\hat{\mathbb{S}}_{PU,L} = \bigcup_{m=1}^{M''} \hat{\mathbb{S}}_{L,m}, \quad \mathcal{R}[\hat{\mathbb{S}}_{PU,L}] = \sum_{m=1}^{M''} \mathcal{R}[\hat{\mathbb{S}}_{L,m}], \quad (10)$$

where  $M'' \geq M'$ ,  $\hat{\mathbb{S}}_{U,m}$  and  $\hat{\mathbb{S}}_{L,m}$  only contain consecutive subcarrier indices.

**Step 3)** The SACM method reaches the final decision set based on the cardinality measuring mechanism below:

$$\hat{\mathbb{S}}_{SACM,m'} = \begin{cases} \hat{\mathbb{S}}_{L,m'}, & \text{if } \exists m \in [1, M'], \hat{\mathbb{S}}_{U,m} \cap \hat{\mathbb{S}}_{L,m'} \neq \emptyset, \\ \emptyset, & \text{if } \forall m \in [1, M'], \hat{\mathbb{S}}_{U,m} \cap \hat{\mathbb{S}}_{L,m'} = \emptyset, \end{cases} \quad (11)$$

where the SACM decision subset  $\hat{\mathbb{S}}_{SACM,m'}$  is either  $\hat{\mathbb{S}}_{L,m'}$  or  $\emptyset$ , depending on whether  $\hat{\mathbb{S}}_{L,m'}$  and  $\{\hat{\mathbb{S}}_{U,m}\}_{m=1}^{M'}$  contain any common element.

**Step 4)** After obtaining  $\{\hat{\mathbb{S}}_{SACM,m'}\}_{m'=1}^{M''}$ , we can finalize the SACM decision set as  $\hat{\mathbb{S}}_{SACM} = \bigcup_{m'=1}^{M''} \hat{\mathbb{S}}_{SACM,m'}$ .

The thresholds  $\lambda_U$ , and  $\lambda_L$  can be determined in Eq. (7) or (8) for different given  $P_{FA,DES}$ , depending on the first-stage algorithm that SACM chooses to follow.  $\lambda_U$  serves to locate the strongest PU-occupied subcarriers (original SA seeds for  $\{\hat{\mathbb{S}}_{U,m}\}_{m=1}^{M'}$ ) with relatively low  $P_{FA,DES}$ . Since  $\lambda_U$  suppresses most false alarms and can only detect the seeds, the SA cardinality of  $\{\hat{\mathbb{S}}_{U,m}\}_{m=1}^{M'}$  is usually small and results in its incapability of detecting the PU-subcarriers with weak strength. Therefore,  $\lambda_L$  is utilized to measure the SA cardinalities of the potential PU subsets  $\{\hat{\mathbb{S}}_{L,m'}\}_{m'=1}^{M''}$ . If any SA seed is identified in  $\hat{\mathbb{S}}_{L,m'}$ ,  $\mathcal{R}[\hat{\mathbb{S}}_{L,m'}]$  is probably the actual cardinality for the subset  $\hat{\mathbb{S}}_{U,m}$  containing the same seed. In this way, many weak PU subcarriers falsely determined as noise-only ones by  $\hat{\mathbb{S}}_{U,m}$  are recovered in  $\hat{\mathbb{S}}_{SACM}$ ; additionally,  $\hat{\mathbb{S}}_{L,m'}$  containing no SA seed stands a good chance to be the noise-only subset. Compared with ISTT, the extra-complexity of the HITT and SACM algorithms only comes from the arithmetic calculations and comparisons in equation (6) and (11), respectively.

## IV. SIMULATIONS

Two wideband PU systems respectively span over 64 and 256 subcarriers and may appear anywhere in the spectrum with rectangular shapes. All the PU-occupied subcarriers are QPSK modulated and subject to independent Rayleigh fading effects. The average SNR is  $\gamma \triangleq \sum_{q \in \mathbb{S}_{PU}} \sigma_q^2 / (Q\sigma_0^2)$ . For ISTT,  $\sigma_0^2$  is perfectly known whereas it is unavailable for HITT.

Given the same  $P_{FA,DES}$ , the HITT algorithm outperforms

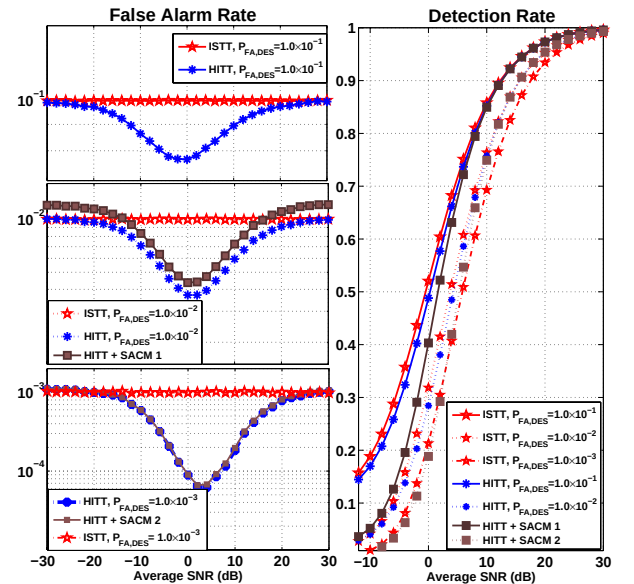


Fig. 1: Performance of SA based wideband sensing schemes, with  $Q = 1024$ ,  $L = 128$ , and  $K = 1$ .

ISTT in terms of false alarm rate, as shown in Figure 1. The

false alarm rate of HITT is much lower than that of ISTT, when the SNR is around  $-10 \sim 10$  dB. This is due to the fact that when some PU-subcarriers are still too weak to be detected, they may be included into  $\hat{S}_0$  and, therefore, boost the EASS of  $S_0$  to suppress some strong noise observations. When the PU signals are sufficiently weak or strong enough (e.g.  $< -10$  dB or  $> 10$  dB), they nearly impose no effect on estimating the EASS of  $S_0$ .

For the same  $P_{FA,DES}$ , the detection rate of HITT closely approaches that of ISTT. The SACM enhances HITT by using  $P_{FA,DES} = 1.0 \times 10^{-1}, 1.0 \times 10^{-2}$  for SACM in case 1, and  $P_{FA,DES} = 1.0 \times 10^{-2}, 1.0 \times 10^{-3}$  in case 2, respectively. The SACM in case 1 possesses a high detection rate very close to that of the ISTT obtained with  $P_{FA,DES} = 1.0 \times 10^{-1}$ , while its false alarm rate only remains the low level of  $P_{FA,DES} = 1.0 \times 10^{-2}$  with marginal degradation. This is the superiority of jointly combining HITT and SACM. The false alarm rate of SACM in case 2 is almost the same as that of HITT with  $P_{FA,DES} = 1.0 \times 10^{-3}$ , because too low  $P_{FA,DES}$  would suppress most false alarms and the SACM in case 2 could not locate as many subsets  $\hat{S}_{L,m}$  as it does in case 1.

## V. CONCLUSION

In this paper, signal assemblage based wideband sensing methods are proposed. Demanding no *a priori* knowledge of the noise and the PU signals, the HITT and SACM methods exhibit a plug-and-play capability and become more accurate and efficient in wideband sensing. They are practically cost-efficient and computationally simple for CR systems with OFDM engines.

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