

Impact of Secondary Users density and Clustering Strategies on Detection of Performance of Spectrum Sharing System

Omotayo M. E., Olusola I. B., Olawale B. O. and Oyajide D. O.

Abstract Accurate spectrum hole detection is essential for cognitive radio networks to avoid interfering with primary users. However, channel impairments often hinder accurate detection of spectrum hole. This paper examines an energy-efficient cooperative spectrum hole detection method that relies on multiple secondary users and clusters to improve detection rates. The study uses an eigenvalue detector in a combined Rayleigh and log-normal fading environment, employing majority and OR fusion rules for local and global sensing, respectively. Simulations in MATLAB R2023a demonstrate that increasing the number of secondary users and clusters enhances detection probability and spectral efficiency, while reducing sensing time.

Keywords: Cognitive Radio (CR), Spectrum Hole (SH), Spectrum Sensing (SS), Probability of Detection (PD) and cluster.

I. Introduction

The widespread adoption of wireless communication has led to a surge in demand, straining the available radio frequency spectrum. This shortage isn't simply due to limited spectrum, but also the traditional fixed spectrum allocation by the International Telecommunication Union (ITU). Licensed users, or primary users (PUs), have exclusive rights, leading to underutilization of assigned frequencies, as spectrum use varies over time. Studies indicate significant periods of inactivity and low average spectrum usage, often below 15% [1, 2, 3, 4, 5]. Given the time and cost of acquiring new spectrum, efficient use of existing allocation is crucial. Cognitive radio (CR) addresses this scarcity by allowing unlicensed users, or secondary users (SUs), to utilize idle spectrum, known as spectrum holes (SHs),

without interfering with PUs. CR's effectiveness hinges on accurate SH detection [6, 7, 8]. Both non-cooperative spectrum sensing (NCSS) and cooperative spectrum sensing (CSS) are employed. NCSS relies on individual SU sensing, while CSS involves multiple SUs sharing sensing results, achieving higher detection rates but with increased sensing time, power consumption, and bandwidth usage [9, 10, 11, 12]. Energy-efficient spectrum hole (EESH) detection aims to mitigate these CSS drawbacks. This paper investigates the impact of SU and cluster numbers on EESH detection using an eigenvalue detector (EVD) in a composite Rayleigh and log-normal fading environment, which accurately models both multipath fading and shadowing effects present in terrestrial wireless channels. While previous research has explored PU detection using individual Rayleigh or log-normal distributions, this study utilizes their combined model for a more realistic representation of CSS conditions [13, 14, 15].

Omotayo, M. E., Oyajide, D. O.

(Department of Electrical/Electronic Engineering, Osun State Polytechnic, Iree, Nigeria)

Olusola, I. B.

(Department of Computer Engineering Technology, Osun State College of Technology, Esa-oke, Nigeria)

Olawale, B. O.

(Department of Computer Engineering Technology, Osun State Polytechnic, Iree, Nigeria.)

Corresponding Author:: mayomot@gmail.com

Phone: +234(0)8037747636

Researchers have explored energy-efficient cooperative spectrum hole detection techniques in cognitive radio networks, primarily aiming to minimize reporting overhead and consequently reduce energy usage, sensing time, and bandwidth consumption. In [16], A hierarchical cluster-based cooperative spectrum sensing (HCB CSS) technique with adaptive thresholds was introduced to improve detection and reduce reporting overhead. This method utilizes an energy detector (ED) with a noise-variance-based adaptive threshold. Secondary users (SUs) are divided into three clusters to minimize reporting overhead, with local sensing data combined using a majority rule and cluster results combined using an OR rule for a global decision. The results demonstrated a decrease in sensing time and an increase in bandwidth efficiency, confirming the reduction of reporting overhead. However, the study did not examine the influence of the number of SUs and clusters on performance.

Also, in [17] a review of energy-efficient cooperative spectrum sensing (EECSS) in cognitive radio (CR) systems highlighted high energy consumption as a key challenge, particularly during local sensing, which also negatively impacts transmission. The review analyzed various algorithms designed to improve energy efficiency in CSS. However, it did not examine the influence of secondary user (SU) and cluster numbers on EECSS. Additionally, a separate study proposed spatial correlation-based EECSS for the Cognitive Internet of Things (CIoT) to minimize reporting overhead and ensure accurate detection. This approach involved clustering SUs before local sensing, with member nodes using an energy detector (ED) and sending results to their cluster heads. A likelihood ratio test with hard fusion was used to obtain the global sensing result, leading to

reduced sensing time and power consumption. Nonetheless, this technique also failed to address the impact of SU and cluster numbers on energy-efficient spectrum hole (EESH) detection. Therefore, this paper investigates the effect of varying SU and cluster numbers on EECSS using an eigenvalue detector (EVD) within a composite Rayleigh and log-normal fading channel.

The eigenvalue detector (EVD) is a non-coherent method that analyzes the eigenvalues of the received signal. It calculates the covariance matrix, determines the maximum and minimum eigenvalues, and then compares their ratio to a predefined threshold to detect the presence or absence of a spectrum hole. [18, 19]. EVD uses a threshold-based comparison of the maximum and minimum eigenvalue ratio to detect spectrum holes. When the ratio matches the threshold, a hole is declared; otherwise, the PU is considered to be transmitting. While EVD is effective for correlated signals, it involves significant computational overhead due to the covariance matrix's formulation and decomposition. Under H_0 hypothesis, the received signal $Y_i(n)$ is given by [20] as Eq. 1

$$Y_i(n) = \sum_{j=1}^M \sum_{k=0}^N h_j(k) x_j(k) + w_j(k) \quad (1)$$

where: M is the number of PU antenna,

N is the number of branch received by individual Antenna

x_j is the PU signals,

$h_j(k)$ is the channel response from PU signal,

$w_j(k)$ is the noise samples.

The sample covariance matrix Y_C is given by [19] as Eq.2

$$Y_C(N) = \frac{1}{Z} H^q H^{+(q)} \quad (2)$$

where: Z is the number of collected samples,

H^q is the square matrix, and $H^{+(q)}$ is the transpose of matrix H^q

According to [21], the characteristic equation of a square covariance matrix H is given as Eq. 3

$$\det(H - \beta I) = 0 \quad (3)$$

where: β is the eigenvalue, and I is the identity matrix.

Cooperative spectrum hole detection (CSDH) involves multiple secondary users (SUs) collectively monitoring the assigned frequency spectrum. These SUs perform sensing operations and share their results to identify spectrum holes (SHs) within the network. [22]. In CSDH, secondary users (SUs) share their detection data to improve accuracy. These individual results are then combined using fusion schemes, with hard fusion (HF) and soft fusion (SF) being the most common. Studies have shown that HF provides better performance while requiring less bandwidth than SF. [5]. This paper utilizes hard fusion (HF) to combine individual secondary user (SU) sensing results. HF involves each SU transmitting a single bit representing their local decision to a fusion center (FC). The FC then employs a linear rule to make a global decision on spectrum hole (SH) presence. Among the common linear rules, the OR rule, which declares a spectrum hole absent if any SU detects activity, is used. While it effectively protects primary users (PUs), it can lead to underutilization of the spectrum. If the total number of sensing system is P and the total number of systems that decides the absence of SH is R , the global probability Q_{OR} is given by [5,23] as Eq.4.

$$Q_{OR} = R - (1 - PD_j)^P \quad (4)$$

Where: PD_i is the probability of detection for the j^{th} sensing system

Cooperative sensing aims to enhance detection accuracy by leveraging the spatial diversity of multiple secondary users (SUs) relative to the primary user (PU). Specifically, using the OR

rule, if any SU detects the spectrum as occupied, the global decision (R) is "1", indicating the absence of a spectrum hole. Therefore, equation (3) becomes

$$Q_{OR} = 1 - (1 - PD_j)^P \quad (4)$$

Conversely, the AND rule declares a spectrum hole absent only if *all* secondary users (SUs) detect occupancy. This maximizes spectrum utilization but compromises primary user (PU) protection against interference. Additionally, the paragraph notes that if 'N' is the total number of SUs performing sensing, and 'K' represents the number of SUs that detect a spectrum hole, then... (the sentence is incomplete, but I've kept the context). In AND rule, $R = M$, therefore, the final probability of detection Q_{AND} is given by [23] as Eq. 5

$$Q_{AND} = (PD_j)^P \quad (5)$$

Majority fusion counts the number of secondary users (SUs) reporting spectrum occupancy and compares it to a threshold. Specifically, a spectrum is deemed occupied if at least $N/2$ SUs indicate it is busy. This approach balances optimal spectrum utilization and primary user (PU) protection. The probability Q_{major} of this rule is given by [5] as Eq. 6

$$Q_{major} = \sum_{K=R}^N \binom{P}{K} P_i^K (1 - PD_j)^{P-K} \quad (6)$$

where: P is the total SU that perform sensing operation

K is the SU that decides the absence of SH

To effectively combine sensing data, majority fusion is utilized among SUs within each cluster, offering a compromise between spectrum efficiency and PU safety. The OR rule is subsequently applied across clusters to ensure maximum protection for licensed users [22].

Clustering in cooperative spectrum sensing (CSS) involves grouping secondary users (SUs)

based on their geographical proximity. Within each cluster, users are designated as either a cluster head (CH) or a cluster member (CM), with the CH being the closest to the fusion center (FC). CSS operates on two levels: an internal, intra-cluster level where CMs perform local sensing and share results with their CH, and an external, inter-cluster level where CHs forward combined sensing data to the FC for a global decision. [5]. The primary goal of clustering in CSS is to alleviate reporting overhead, which leads to congestion, and to decrease computational complexity, which results in high energy usage [24].

II. Materials and Method

A. Composite Rayleigh and log-normal fading channel

For this investigation, a composite Rayleigh and log-normal fading channel, illustrated in Figure 1, is employed. Rayleigh and log-normal fading components are represented by h_1 and h_2 , respectively. The composite channel model is employed to examine how the number of secondary users (SUs) and clusters affects energy-efficient cooperative spectrum hole (EECSH) detection. The PDF of the composite fading channel ' $P_{RL}(r)$ ' is given as Eq. 7

$$P_{RL}(r) = \int_0^\infty P_R(r) \cdot P_L(r) dr \quad (7)$$

where: $P_R(r)$ is the PDF of Rayleigh fading channel

$P_L(r)$ is the PDF of log-normal fading channel

The probability density functions (PDFs) of Rayleigh and log-normal fading channels are used to derive the expression for the composite fading channel employed in this study as shown in Eq. 8.

$$P_{RL}(r) = \int_0^\infty \frac{r}{\sigma^2} \exp\left(-\left(\frac{r^2}{2\sigma^2}\right)\right) \frac{10/\ln 10}{r\sigma(2\pi)^{1/2}} \exp\left(-\frac{(\ln r - \mu)^2}{2\sigma^2}\right) dr \quad (8)$$

By solving Equation (8), the closed form expression of the $P_{RL}(r)$ gives Eqns. 9-13.

$$P_{RL}(r) = \frac{1.733}{\sigma^3} \left(\exp\left(-\frac{\mu}{2\sigma^2}\right) \sigma^3 \left(\frac{\pi}{2}\right)^{1/2} \right) \quad (9)$$

$$P_{RL}(r) = \frac{1.733}{\sigma^3} \left(\exp\left(-\frac{\mu}{2\sigma^2}\right) \sigma^3 \left(\frac{(2\pi)^{1/2}}{2}\right) \right) \quad (10)$$

$$P_{RL}(r) = \frac{1.733}{\sigma^3} \left(\exp\left(-\frac{\mu}{2\sigma^2}\right) \sigma^3 \left(\frac{(2\pi)^{1/2}}{2}\right) \right) \quad (11)$$

$$P_{RL}(r) = \frac{1.733}{2} \left(\exp\left(-\frac{\mu^2}{2\sigma^2}\right) (2\pi)^{1/2} \right) \quad (12)$$

$$P_{RL}(r) = 0.8665 \left((2\pi)^{1/2} \exp\left(-\frac{\mu^2}{2\sigma^2}\right) \right) \quad (13)$$

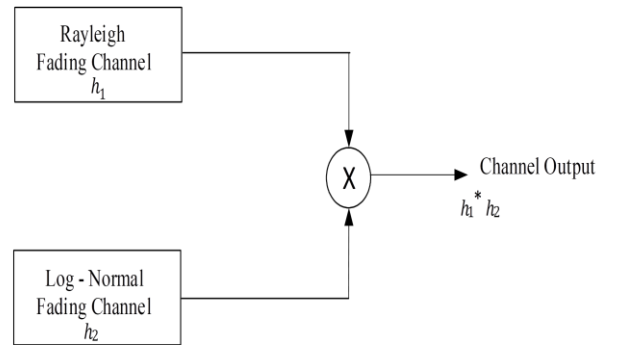


Figure 1: Composite Rayleigh and Log-Normal Fading Channel

B. Energy Efficient Cooperative Network

This study investigates the impact of secondary users (SUs) and clusters on energy-efficient cooperative spectrum hole (EECSH) detection. The experiment uses multiple SUs and clusters, specifically SUs and clusters, with each cluster

containing SUs and a cluster head (CH), as illustrated in Figure 1. The distance between each SU and its corresponding CH is determined by the cluster radius denoted as R_C given by [25] as Eq. 14

$$R_C = \frac{\varnothing-1}{\varnothing+1} CA_{PU} \quad (14)$$

where: CA_{PU} is the licensed user coverage area
 $\varnothing = 10^{\frac{0.1}{\delta}}$

δ is the path loss exponent of the environment

This investigation models an urban environment, using a path loss exponent of 3.1, as established in previous research [9]. Equation (14) is then solved with this specific path loss exponent value., cluster radius is obtained as

$$R_{C/urban} = 0.037 CA_{PU} \quad (15)$$

The distance between SUs and their CHs is determined by Equation (15). Majority fusion is then used at each CH to decide if a spectrum hole (SH) exists, as it offers a compromise between protecting PUs and maximizing spectrum usage.

C. Probability of Detection (PD)

Probability of detection (PD) represents the system's accuracy in identifying spectrum holes (SHs). A higher PD indicates better system performance, so maximizing PD is crucial. In this study, sensing within individual clusters is referred to as local sensing. Therefore, the PD expression at local sensing PD_L is obtained as

$$PD_L = \Pr(T > 1) \quad (16)$$

where: T is the ratio of maximum to minimum eigenvalue of the PU signal

Using equations (6) and (16), the probability of detection at each cluster $PD_{CL,major}$ is obtained as

$$PD_{CL,major} = 2^{K-1}(P+2)(1-PD_L)^K(1-(1-PD_L))^{P-K} \quad (17)$$

At the global decision, OR fusion rule is used due to better PU protection. Using Equations (4), the global PD ' $PD_{GL,OR}$ ' is obtained as

$$PD_{GL,OR} = 1 - (1 - PD_{CL,major})^M \quad (18)$$

By substituting Equation (17) into (18), the global PD is obtained as

$$PD_{GL,OR} = 1 - (1 - 2^{K-1}(P+2)(PD_L)^K(1-PD_L)^{P-K})^P \quad (19)$$

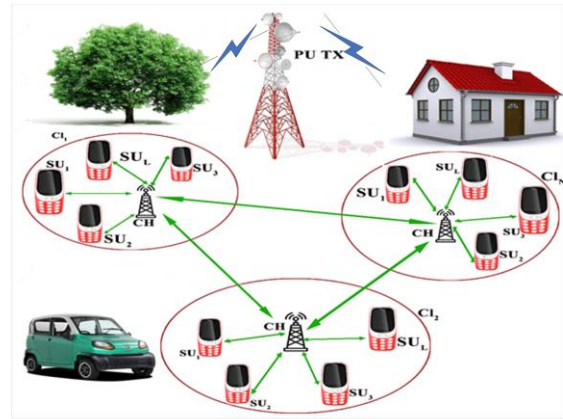


Figure 2: Energy Efficient Cooperative Spectrum Hole (EECSH) Detection Network Model

D. Spectral Efficiency

Spectral efficiency (SE) quantifies how effectively a communication system transmits signals within a given bandwidth. It indicates the utilization efficiency of the available spectrum and reflects the bandwidth efficiency of the system. Spectral efficiency 'SE' is given by [12] as

$$SE = \frac{CP}{BW} \quad (20)$$

where: CP is the channel capacity

BW is the channel bandwidth

Channel capacity CP is given as

$$CP = BW \log_2(1 + SNR) \quad (21)$$

Substituting Equation (15) into (14) gives

$$SE = \log_2(1 + SNR) \quad (22)$$

where: SNR is the signal strength of the received PU signal.

III. Results and Discussion

The system was simulated in MATLAB R2018 using 20,000 runs with varying seed values within a composite Rayleigh and log-normal fading channel. Figure 3 illustrates the probability of detection (PD) against the number of clusters at a fixed signal-to-noise ratio (SNR) of 20 dB. At a cluster count of 3, PD values were 0.7367, 0.7517, and 0.7607 for 4, 5, and 6 secondary users (SUs), respectively. With 5 clusters, the corresponding PD values were 0.8293, 0.8432, and 0.8523. The results demonstrate that PD increases with both the number of clusters (due to reduced hidden node problems) and the number of SUs per cluster (due to decreased receiver uncertainty).

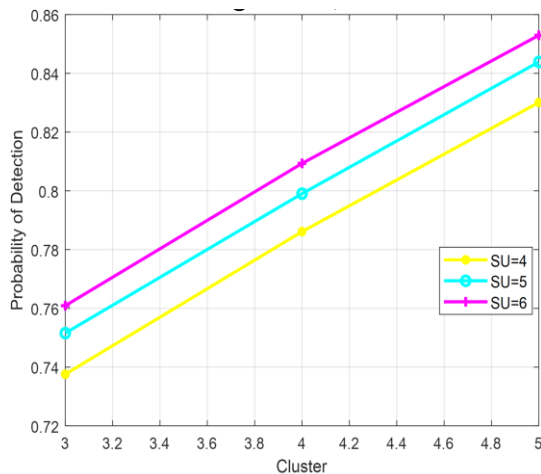


Figure 3: Probability of Detection (PD) versus Cluster at SNR of 20 dB with Different Number of SU over Composite Rayleigh and Log-Normal Fading Channel

Figure 4 illustrates the impact of secondary user (SU) and cluster numbers on spectral efficiency (SE) at varying signal-to-noise ratios (SNRs). At a 10 dB SNR, SE increased with both SU and

cluster count. For instance, with 3 clusters, SE rose from 8.6273 to 11.6261 bps/Hz as SU numbers increased from 4 to 6. Similarly, with 5 clusters, SE increased from 11.8021 to 14.8009 bps/Hz. This indicates improved bandwidth efficiency with higher SU and cluster numbers. Figure 5 demonstrates that sensing time (ST) decreases as cluster numbers increase, suggesting enhanced energy efficiency. However, SU numbers had no noticeable effect on ST. Therefore, to maximize detection rates without increasing sensing time, a higher number of SUs within each cluster is recommended.

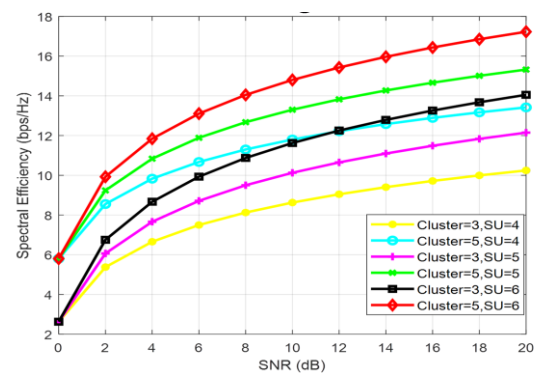


Figure 4: Spectral Efficiency (SE) versus SNR at Different Number of Clusters and SUs over Composite Rayleigh and Log-Normal Fading Channel

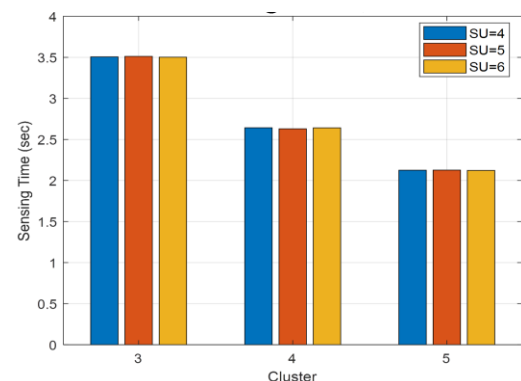


Figure 5: Sensing Time (ST) versus Cluster at Different Number of SUs over Composite Rayleigh and Log-Normal Fading Channel

IV. Conclusions

This paper examined the impact of secondary user (SU) and cluster numbers on energy-efficient spectrum hole (EESH) detection within a composite Rayleigh and log-normal fading channel. Performance was evaluated using probability of detection (PD), spectral efficiency (SE), and sensing time (ST). Clusters were formed using multiple SUs and a cluster radius. Majority fusion was used within clusters, and OR fusion between clusters, for global decision-making. The influence of SU and cluster numbers on EESH detection was investigated in a composite fading channel, using PD, SE, and ST as metrics. Clusters were formed, and sensing results were combined using majority and OR fusion rules. The study found that PD and SE improved with more SUs and clusters, while ST decreased with more clusters, remaining unaffected by SU numbers. The results showed that PD and SE increased with higher SU and cluster numbers, while ST decreased with more clusters. However, SU numbers did not affect ST. Consequently, increasing both cluster and SU numbers improves energy and bandwidth efficiency and detection rates, making high SU and cluster counts desirable in EESH design. Therefore, maximizing both SU and cluster numbers is recommended for enhanced detection, energy, and bandwidth efficiency in EESH system design.

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