Energy-Efficient Cluster-Based Cooperative Spectrum Sensing in a Multiple Antenna Cognitive Radio Network

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***Abstract*—Spectrum Hole Detection (SHD) is a major operation in a Cognitive Radio (CR) network to identify empty spectrum for maximum utilization. However, SHD is often affected by multipath effects resulting in interference. The existing techniques used to address these problems are faced by poor detection rate, long sensing time and bandwidth inefficiency. Hence, this paper proposes a cluster-based Energy-Efficient Multiple Antenna Cooperative Spectrum Sensing (EEMACSS) for SHD in CR networks using Energy Detector (ED) with a modified combiner. Multiple secondary users are used to carry out local sensing using ED in multiple antenna configurations. The local sensing results are combined at the cluster head using majority fusion rule to determine the sensing results at each cluster. The sensing results from individual cluster are combined to determine the global sensing result using OR fusion rule. The proposed EEMACSS is evaluated using Probability of Detection (PD), Sensing Time (ST) and Spectral Efficiency (SE) by comparing with existing techniques. The results reveal that the proposed technique shows better performance.**

***Index Terms*—Cluster, Cooperative Spectrum Sensing (CSS), Energy Detector (ED), Multiple Antenna (MA), Primary User (PU), Secondary User (SU)**

I. INTRODUCTION

Wireless communication is experiencing a strong expansion due to its deployment in many facets of human endeavor and this make the demand for radio spectrum to rise exponentially. In order to meet the explosive growth of the wireless users, it is recommended to deploy 5G technology which is expected to support higher data traffic as against the already deployed Long Term Evolution (LTE). Therefore, the daily increase in demand for radio spectrum has given rise to a great need for more spectrum that results in spectrum scarcity [1]-[3]. Spectrum scarcity which is unavailability of radio spectrum, is not only due to insufficient spectrum but also to the fixed spectrum access that gives only licensed users privilege to utilize its spectrum as no other users can access it. However, several portions of the allocated spectrum are not used over a considerable periods and average usage of some spectrum is below 15% [1]. Since the regulatory process of the new radio spectrum is time consuming, therefore, the efficient use of available spectrum is of paramount importance in solving problem of spectrum scarcity in wireless communication. Cognitive Radio (CR) system is proposed to address the problem of unavailability of spectrum by allowing unlicensed user to exploit the licensed spectrum when it becomes idle [2]. CR senses the licensed spectrum over a certain frequency band to detect unused spectrum and opportunistically provide communication links through the unused spectrum. It improves utilization of spectrum by enabling unlicensed users access the licensed spectrum without interfering with the licensed users [3]-[6]. H_1 and H_2 are the two hypotheses that indicate the presence and absence of licensed user signal, respectively. The sensing of spectrum otherwise known as Spectrum Sensing (SS) makes unlicensed user scans through the spectrum to ascertain the presence of the licensed user and identify spectrum hole in a CR. Also, the performance of CR depends on the ability of the unlicensed user to detect idle spectrum and transmit signal through the detected spectrum without causing interference to licensed user [7], [8].

Single Antenna (SA) and Multiple Antenna (MA) are the two antenna configurations used for spectrum sensing. In SA, only one antenna is used at both PU and SU, while MA involves SA at PU and MA at SU. MA performs relatively better than SA due to increase in PU signal strength but requires a diversity combiner to combine the multiple copies of PU signal [9]. Non-Cooperative SS (NCSS) and Cooperative SS (CSS) are two major sensing techniques used in CR network [8], [9]. NCSS is a sensing technique in which only one SU performs the sensing and making decision on its own, while CSS is one of the sensing techniques in which group of SUs share the sensed information among one another. In order to improve detection rate of both NCSS and CSS, MA configuration is introduced into architecture of sensing operation using two or more antennas. However, Multiple Antenna Cooperative SS (MACSS) shows better performance with higher detection rate than Multiple

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Antenna Non-Cooperative SS (MANCSS) due to receiver uncertainty when SU is outside the coverage area of PU signals but at expense of long sensing time, high power consumption and bandwidth inefficiency [10]. Therefore, the existing works suffered from receiver uncertainty when single SU was used to perform spectrum sensing and large signaling overhead resulting in long sensing time. Bandwidth and energy inefficiency were the effects of two or more SUs jointly used. The long sensing time and high-power consumption are due to the hardware complexity of combiner used to combine the multiple copies of PU signals before applying ED, while bandwidth inefficiency is due to only large signaling overhead during fusion in combining the sensing results from individual SU. Hence, in this paper, cluster-based Energy Efficient MA CSS (EEMACSS) is proposed to reduce sensing time and power consumption with bandwidth efficiency using ED with a modified combiner. One of the features of the 5G is energy efficiency which increases the revenue of service providers by reducing operational expenditure through saving on the electricity bills thereby reducing the joule per bit cost that keeps mobile services affordable for the users. Therefore, the system that has a low power consumption is required to make the proposed 5G network services affordable for all mobile users. The contributions of this paper are as follows:

1) The formation of cluster in the proposed technique is based on distance between PU and Cluster Head (CH) which gives accurate placement of SU based on the coverage area. To the best of authors' knowledge, no work has been done on cluster formation in multiple antenna cooperative spectrum sensing using distance between PU and CH. The formation of cluster is usually based on random distribution resulting in excess or insufficient SU.

2) The technique proposes a new local sensing technique with reduced hardware complexity which affects reduces the overall sensing time and power consumption of the proposed technique. This is achieved using Equal Gain Combiner (EGC) with single RF chain and single Matched Filter (MF) to combine the multiple copies of PU signals before applying ED.

3) SU selection is carried out in the proposed technique to reduce power consumption. The reduction in power consumption leads to increase in the revenue of the service provider by reducing operational expenditure through saving on the electricity bills. The saving on electricity bills results in reduction of the joule per bit cost that keeps mobile services affordable for the users. To the best of authors' knowledge, this has not been investigated.

4) The proposed technique focuses on bandwidth efficiency which is evaluated using Spectral Efficiency (SE). SE for the proposed work is derived in this work. The derivation of SE has not been carried out in any existing multiple antenna cooperative spectrum sensing.

5) The derivation of the Probability of False Alarm (PFA) expression for the new local sensing is carried out using Chi-square distribution. The PFA derived is used to set decision thresholds at 0.1 and 0.01 to determine the effect of PFA on the proposed technique.

The remaining of this paper is organized as follows; Conventional MACSS (CMACSS) technique with fusion technique that combines the sensing results from individual SU is presented in Section II. While, Section III presents the review on the existing related work. Section IV presents proposed EEMACSS that includes improvement of ED for local sensing, SU selection that select the SUs that participate in the local sensing, decision threshold, detection rate for local sensing and cluster formation to reduce the signaling overhead. Section V depicts the simulation results as well as performance comparison, while Section VI concludes the paper.

II. Conventional MACSS

In order to determine the global sensing results through fusion, the CMACSS technique in which individual SU carries out local sensing using multiple antenna and share the local sensing results among one another is adopted. Unlike Multiple Antenna Non-Cooperative Spectrum Sensing (MANCSS) in which only one SU carries out sensing operation and makes decision on its own using multiple antenna [7]. MANCSS suffers from receiver uncertainty that occurs when SU is not within the transmission range of licensed user resulting in harmful interference from SU to PU [3]. In CMACSS, the local sensing involves combining the multiple copies of PU signal using diversity combiners such as EGC and Selection Combiner (SC) before applying ED [11]. The purpose of CMACSS is to improve the detection rate by combining sensing information from spatially located SUs and achieving more accurate decision than NCSS [12]. It solves the challenges of MANCSS through spatial diversity, thereby achieving a reliable detection that mitigates interference from SU to PU since it is not possible for all spatially located SUs in a CR network to experience signal fluctuation at the same time. Also, CMACSS allows SUs to jointly carry out SS to enhance detection rate even at a very low PU signal strength thereby providing a reliable spectrum usage over the band where the CRs are located [10], [13], [14].

The results of local sensing from individual SU are combined using fusion rule. The two commonly used fusion techniques are Soft Fusion (SF) and Hard Fusion (HF). Previous researches on fusion technique revealed that HF gives better performance in term of bandwidth efficiency when compared with SF. Therefore, in this paper HF is used to combine the local sensing results [7]. HF is a technique in which the decisions from local sensing are sent as one-bit among SUs to make overall decision on the idleness of PU spectrum. In this fusion rule, each SU determines sensing results and forward the results to Fusion Centre (FC). The results received by FC, are then processed using a linear rule to determine final decision. The three basic linear rules used in the literature are AND, OR and majority rule. In OR rule, the spectrum is busy if at least one of the SUs identifies that spectrum is not idle. The rule protects the licensed user but suffers from poor utilization of spectrum. If the total number of SUs is N and the total number of SU that decide the occupancy of spectrum is R, the global probability Q_{OR} is given by [7], [15] as

$$Q_{OR} = R - (1 - p_i)^N \quad (1)$$

where p_i is the probability of detection for the i^{th} SU.

In OR rule, $R = 1$ since spectrum is busy, if at least one of SUs decides that the spectrum is occupied. Therefore, equation (1) becomes

$$Q_{OR} = 1 - (1 - p_i)^N \quad (2)$$

In AND rule, the spectrum is busy if all the SUs decide that the spectrum is occupied. The rule provides maximum spectrum utilization but at the expense of poor licensed holder protection. Also, if the total number of SUs is N and the total number of SUs deciding the idleness of spectrum is R. Since $R = N$ in AND rule, the global probability Q_{AND} is given by [15] as

$$Q_{AND} = (p_i)^N \quad (3)$$

Majority fusion rule counts the number of SU that identify the presence of licensed user and compared the result with the predefined threshold. In this rule, the spectrum is busy, if at least R of SUs decide that spectrum is occupied. This rule maintains a balance between spectrum utilization efficiency and licensed user protection. The probability Q_{major} of this fusion is given by [7] as

$$Q_{major} = \sum_{K=R}^{N} \binom{N}{K} p_i^l (1 - p_i)^{N-K} \quad (4)$$

where N is the total number of SUs and K is the SU that decides the presence of PU.

Majority fusion rule approaches AND rule when the detection threshold is too small and approaches OR rule when the detection threshold is very high. Therefore, the rule maintains a balance between spectrum utilization and PU protection, which proves to be an optimum fusion rule in CSS. In this paper, majority rule is used between SUs within a cluster due to harmonization of other two rules and OR rule is used between clusters due to high PU protection [11].

III. Related Works

There have been various existing works on multiple antenna spectrum sensing in CR networks for detection of PU signal. Authors in [10] modified square law combiner by replacing several Energy Detectors (EDs) with single ED to address interference caused by SU to PU in a CR network. The multiple copies of PU signal are combined using threshold combiner before applying ED to obtain the energy of PU signal and compared with the set threshold to determine the idleness of spectrum. The results obtained revealed that, the technique gave a low detection rate when compared with CSS due to hidden node problem which caused multipath fading and shadowing effect. Non-Cooperative SS (NCSS) in context of PU detection is proposed in [16]. The work focused on solving PU interference in CR using ED with multiple antenna. Multiple SU antenna received the multiple copies of PU signal and combined using Selection Combiner (SC). Signal output of SC was used as input to ED to obtain the energy of the PU signal. The obtained energy was compared with the set threshold to determine the idleness of spectrum. The results obtained revealed that, the technique gave poor detection rate when compared with CSS approach due to receiver uncertainty. In [17], a dynamic dual threshold CSS for CR in the presence of noise power uncertainty. The work focused on threshold mismatch of ED under noise power uncertainty using dynamic dual threshold. EGC combined the multiple copies of the PU signal which is then used as input to the ED to determine the energy of the combined signal. Upper and lower thresholds were set as decision threshold based on false alarm probability. The energy obtained was then compared with the set thresholds to identify the presence and absence of PU signal. The technique showed an improvement in the detection rate when compared to conventional ED but at the expense of large reporting overhead which increased as the number of SU increased, thereby resulting in power inefficiency and long sensing time.

Furthermore, optimization of spectrum utilization in CSS was proposed in [18]. The work focused on solving receiver uncertainty resulting in harmful interference in a CR system using ED. Multiple SUs were jointly used to carry out SS and individual SU performed local sensing using ED. The outputs of ED from individual SU were sent to Fusion Center (FC) and combined using soft fusion. The combined sensing result was compared with the set threshold to make final decision. Optimization was carried out using Poisson process to maintain a trade-off between spectrum utilization and transmission time. The technique gave an average detection rate, however, it suffered from high signaling overhead resulting in bandwidth inefficiency, long sensing time and high-power consumption. In [19], a blind and soft fusion detector for CSS was proposed to solve the problem of hidden terminal during spectrum sensing using spatial diversity in CR networks. Multiple SUs were spatially distributed to jointly carry out SS. Individual SU carried out local sensing using ED and soft fusion scheme. Quade test in which only the power and variance of instantaneous power at individual SU was required for global decision at the FC. The combined information at FC was then compared with the set threshold to make final decision on the presence or absence of PU. The results obtained revealed that, the proposed technique gave a higher PD when compared to NCSS. However, the technique suffered from bandwidth inefficiency due to soft fusion implemented in the system. On the other hand, CSS for CR networks was presented in [20] to reduce PU interference in CR system using centralized CSS approach. Five SUs were used to carry out local sensing using ED and the sensed decisions were sent to fusion center using hard decision. At the global sensing, the results of local sensing were combined using OR and AND rules. The study revealed better performance of CSS with higher PD and lower PM than NCSS. However, the technique required backbone infrastructure due to fusion center used resulting in increased in hardware complexity.

IV. Proposed Cluster-Based EEMACSS

The proposed Energy Efficient MACSS (EEMACSS) is achieved by incorporating ED in a modified EGC within CMACSS in a cluster-based system to enhance the performance of CMACSS through reduction in hardware complexity and signaling overhead. SU selection is firstly carried out to select the SU that participates in local sensing based on the set threshold of 1dB. Local sensing is then carried out on the selected SU using ED with the modified EGC in a multiple antenna system. Decision threshold for local spectrum sensing is set, based on the derived mathematical expression for PFA. Thirty (30) SUs are used to form five (5) clusters to reduce signaling overhead during fusion. The proposed technique is evaluated using Probability of Detection (PD), Sensing Time (ST) and Spectral Efficiency (SE) to determine its performance.

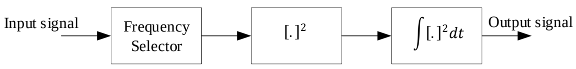

Fig. 1. Diagram of ED for a single antenna system [10].

A. Energy Detector with a Modified Equal Gain Combiner

Energy Detector (ED) uses the energy of PU signal to identify the idleness of the licensed spectrum. It is the simplest detector to identify the licensed user in CR network and does not require any prior information about the PU for implementation. In ED, detection of PU signal is achieved by comparing the energy of the received PU signal with the decision threshold, which depends on the noise variance [10]. Fig. 1 presents the diagram of ED in a single antenna system. The frequency selector allows frequencies of a certain range to pass while attenuating the other frequencies [11]. The signal output of frequency selector is squared and integrated over a period to determine the energy of the input signal. The obtained energy is then compared with the decision threshold to check the spectrum status for idleness or otherwise [10].

The performance of ED increases as the signal strength of PU increases. Therefore, diversity combiner that combines the multiple copies of the signal at the SU node is incorporated to improve signal strength thereby improving detection rate of ED. The diversity combiners commonly used with ED are EGC and SC which combine the multiple copies of the PU signal before applying detector. Previous work on ED revealed that, EGC showed a better performance than SC but suffers from hardware complexity. The hardware complexity of EGC is due to multiple Radio Frequency (RF) chains and Match Filters (MFs) involved that cause long sensing time [11]. Therefore, the existing ED is improved by replacing the multiple RF chain and MF of EGC with single RF chain and MF known as a modified EGC in this paper, to reduce the hardware complexity of existing ED, which subsequently reduces the sensing time. Output of ED, E without combiner is given by [21] as

$$E = \sum_{n=1}^{M} |u(n)|^2 \tag{5}$$

$$E \geq \gamma \tag{6}$$

where M is the periodic duration of the selected signal, $u(n)$ is the SNR of PU signal, γ is the set threshold.

Equation (5) indicates whether PU spectrum is idle or occupied. If E is higher than the set threshold, the decision indicates the occupancy of spectrum, otherwise, the spectrum is idle.

The output signal-to-noise ratio (SNR) of EGC SNR_{EGC} is given by [21], [22] as

$$SNR_{EGC} = \frac{1}{wL}\left(\sum_{i=1}^{L} S(i)\right)^2 \tag{7}$$

where $S(i)$ is the received signal on each branch, L is the number of branches, and w is the noise present on each branch.

Therefore, when EGC is incorporated with ED, the output of ED 'E_{EGC}' is given as

$$E_{EGC} = \sum_{n=1}^{N} \left|\frac{1}{wL}\left(\sum_{i=1}^{L} S_n(i)\right)^2\right|^2 \tag{8}$$

B. Secondary User (SU) Selection Process

According to Malhotra *et al*. [13], the probability of detecting a signal that has SNR below 1dB is approximately equal to zero. This assumption is adopted as well in this paper. Therefore, when the SNR of the signal received at a particular SU is below 1dB, local sensing of such SU will have little or no effect on the global sensing rate rather than increasing the power consumption of the system. The SNR of the received signal at individual SU is determined using channel gain and noise present on the received signal. The value of SNR obtained is then compared with the set threshold. If the SNR is less than the set threshold, such SU will be on sleep mode, otherwise, the SU will participate in the local sensing. The selection of SU for the proposed technique is based on the signal strength as depicted in Algorithm 1.

Algorithm 1: SU selection Algorithm

Begin
define: P_t is PU transmit power,
    W is noise present,
    H is channel gain.
Initialize P_t, W, H
compute SNR of the PU signals using $\gamma = \frac{P_t H}{W}$
if ($\gamma \geq 1\ dB$) **then**
    SU carries out local sensing
else
    SU remains idle
end
End

C. Local Sensing Using ED with a Modified EGC

The multiple copies of PU signal are received by SU antennas, EGC with single RF chain and MF is used to combine the multiple copies of PU signals at RF stage. Output of EGC is then applied to ED as depicted in Fig. 2 and h_{ri} is the channel gain from PU signal.

The multiple PU signals received by SU antennas are weighted separately using RF weighting factor before summing. In order to determine the energy of PU signal, the resultant output signal is then made to pass through RF chain and MF to remove any unwanted signals that is present before applying ED. The obtained energy and decision threshold are then compared with each other to determine the status of PU spectrum. If the obtained energy is higher than the decision threshold, then spectrum is occupied due to PU signal's ongoing transmission, otherwise, spectrum is idle. The decision threshold is set at PFA of 0.01 and 0.1. The received signal $S(i)$ at individual SU antenna is given as

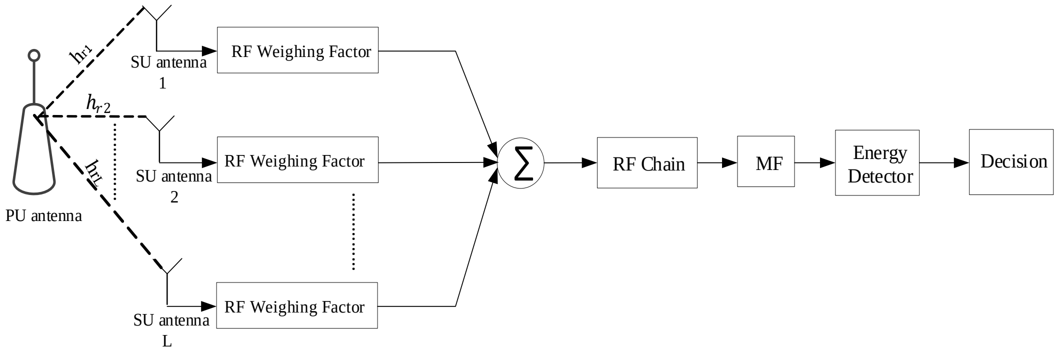

Fig. 2. Block diagram of the proposed technique for local SS.

$$S(i) = V(i) + W(i) \tag{9}$$

where $V(i)$ is the PU signal power on each branch and $W(i)$ is the noise present on individual branch.

Using Equations (8) and (9), the output of ED E_{EGC} yields

$$E_{EGC} = \sum_{n=1}^{N} \left| \frac{1}{wL} \left(\sum_{i=1}^{L} V(i) + W(i)\right)^2 \right|^2 \tag{10}$$

Spectrum decision then uses test statistic given in equation (6) to decide whether the spectrum is busy or idle.

1) Decision threshold for local sensing

The decision threshold of local sensing for the proposed technique is determined using PFA which is derived as follows.

According to [22], the total noise power w_{tot} at the output of the modified EGC is given as

$$w_{tot} = \sum_{i=1}^{L} a_i w_i \tag{11}$$

where a_i is the weight on each branch and w_i is the noise power on each branch.

Using Equations (5) and (11), output of ED E_{EGC} under H_0 hypothesis is given as

$$E_{EGC/H_0} = \sum_{n=1}^{N} \left| \sum_{i=1}^{L} a_i(n) w_i(n) \right|^2 \tag{12}$$

Since E_{EGC/H_0} is the sum of square, the test statistic distribution, therefore, becomes a X^2 distribution. Using X^2 distribution, the output of ED $'f_{EGC/H_0}(\xi)'$ [21] is given by (13), where: σ_i is the noise variance and $\Gamma(.)$ is the gamma function.

To obtain PFA, Equation (14) is integrated with respect to the degree of freedom ξ. By solving (14), PFA yields (15) and (16).

$$f_{EGC/H_0}(\xi) = \frac{1}{\left(\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)\right)^{\frac{N}{2}} 2^{N/2}\Gamma(N/2)} \xi^{(N/2)-1} \exp\left(-\frac{\xi}{2\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)}\right) \tag{13}$$

$$PFA_{EGC} = \frac{1}{\left(\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)\right)^{\frac{N}{2}} 2^{N/2}\Gamma(N/2)} \int_{\frac{\lambda}{2\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)}}^{\infty} \xi^{(N/2)-1} \exp\left(-\frac{\xi}{2\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)}\right) d\xi \tag{14}$$

$$PFA_{EGC} = \frac{2^{N/2}\left(\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)\right)^{\frac{N}{2}}}{\left(\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)\right)^{\frac{N}{2}} 2^{N/2}\Gamma(N/2)} \int_{\frac{\lambda}{2\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)}}^{\infty} t^{(N/2)-1}\exp(-t)\, dt \tag{15}$$

$$PFA_{EGC} = \frac{1}{\Gamma(N/2)} \int_{\frac{\lambda}{2\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)}}^{\infty} t^{(N/2)-1}\exp(-t)\, dt \tag{16}$$

Using incomplete gamma function given by [12] as

$$\Gamma(a,b) = \int_{a}^{\infty} t^{b-1}\exp(-t)dt$$

Equation (16) becomes

$$PFA_{EGC} = \frac{\Gamma\left(\frac{\lambda}{2\sum_{n=1}^{N}\sum_{i=1}^{L}\sigma_i^2(n)}, N/2\right)}{\Gamma(N/2)} \tag{17}$$

2) Detection rate for local sensing

Detection rate which is the Probability of Detection (PD) describes the chances of making the right decision on the presence of PU signal. The higher the value of PD the better the performance of the system. Therefore, to determine the PD, the energy of the received signal is obtained using (10) and then compared with the decision threshold. Equation (17) is used to obtain the threshold at different PFAs. If the obtained energy is higher than the decision threshold, then, the PU spectrum is occupied, otherwise, the spectrum is idle. Therefore, in this paper, the PD for the local sensing PD_L is given as

$$PD_L = \Pr(E_{EGC} > \lambda) \tag{18}$$

The PDs obtained from (18) are then combined at the cluster using majority fusion rule due to its ability to compromise between PU protection and spectrum management efficiency.

D. Formation of Cluster for the Proposed Technique

The proposed cluster formation is to reduce the signaling overhead between SUs thereby reducing the long sensing time, bandwidth inefficiency and high-power consumption. In this paper, five clusters are considered and each cluster contains six SUs with a CH as shown in Fig. 3. The distance between the individual SU and a CH is determined using cluster radius R given by [7] as

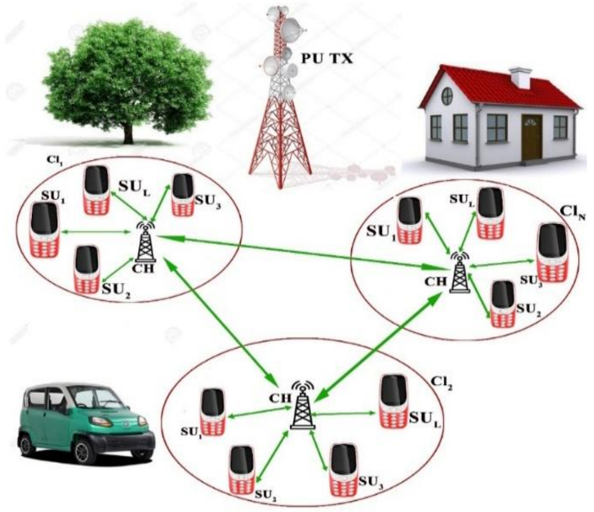

Fig. 3. Architecture of the proposed EEMACSS technique.

$$R_C = \left(\frac{\left(10^{\frac{0.1}{\alpha}}\right)-1}{\left(10^{\frac{0.1}{\alpha}}\right)+1}\right) D_P \tag{19}$$

where D_P is the distance between the PU and CH, α is the path loss exponent which is 3.1 for urban environment [23].

Solving (19) using the value of the path loss exponent for urban environment, cluster radius is obtained as

$$R_C = 0.037 D_P \tag{20}$$

At each cluster, majority fusion rule is used to make decision on the idleness of PU spectrum at the CH due to its compromise between the spectrum management efficiency and PU protection.

Using equations (4) and (18), the PD at the cluster PD_{CL} yields

$$PD_{CL} = \sum_{K=R}^{N} \binom{N}{K} (p_i D_L)^K (1 - p_i D_L)^{N-K} \tag{21}$$

Solving equation (21), gives the PD_{CL} as

$$PD_{CL} = 2^{K-1}(N+2)(p_i D_L)^K (1 - p_i D_L)^{N-K} \tag{22}$$

E. Spectral Efficiency (SE) of the Proposed EEMACSS

The Spectral Efficiency SE which describes the bandwidth efficiency of a system is given by [24] as

$$SE = \frac{C}{B} \tag{23}$$

where C is the channel throughput and B is the bandwidth.

The channel throughput in (23) is given by [25] as

$$C = B\log_2(1 + SNR) \tag{24}$$

Substituting equation (7) into (24) yields

$$C = B\log_2\left(1 + \frac{1}{wL}\left(\sum_{i=1}^{L} S(i)\right)^2\right) \tag{25}$$

Using (23) and (25), the spectral efficiency for the proposed EEMACSS technique is obtained as

$$SE = \log_2\left(1 + \frac{1}{wL}\left(\sum_{i=1}^{L} S(i)\right)^2\right) \tag{26}$$

The proposed EEMACSS technique is simulated using MATLAB software.

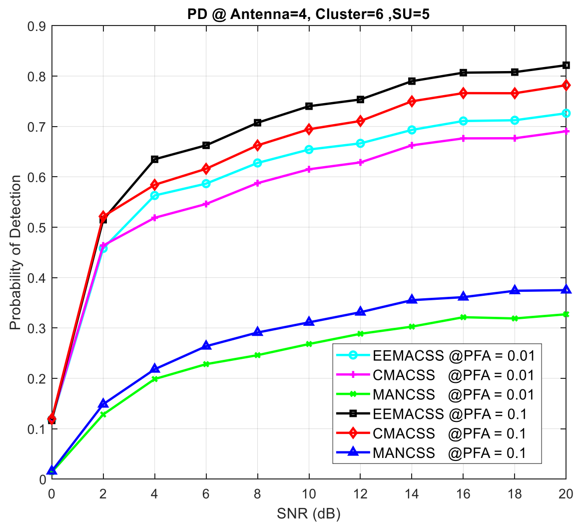

Fig. 4. PD against SNR for EEMACSS, CMACSS and MANCSS at different PFAs with four SU antennas.

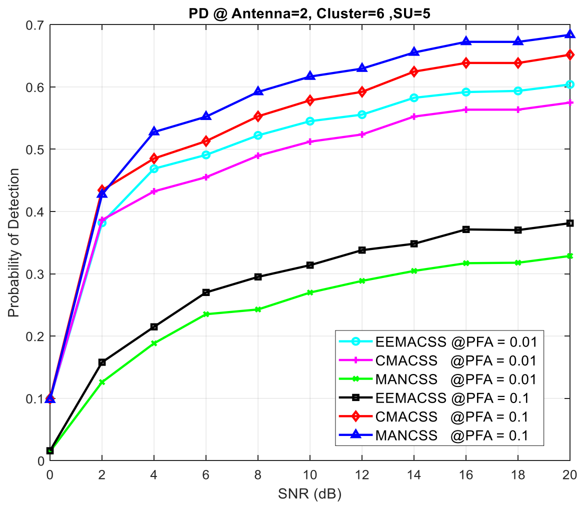

Fig. 5. PD against SNR for EEMACSS, CMACSS and MANCSS at different PFAs with two SU antenna.

V. Simulation Results

Figs. 4 and 5 present the PD against SNR for EEMACSS, CMACSS and MANCSS with different PFAs at SU antenna of 4 and 2. Fig. 4 shows the PD against SNR for EEMACSS, CMACSS and MANCSS at PFA of 0.01 with SU antenna of 4. The PD values obtained at SNR of 10 dB for EEMACSS, CMACSS and MANCSS are 0.7933, 0.7458 and 0.2703, respectively at PFA of 0.01, while at SNR of 16 dB, PD values of 0.8614, 0.8211 and 0.3199 are obtained for EEMACSS, CMACSS and MANCSS, respectively. The results obtained reveal that, detection rate increases as SNR increases and this is due to the inclusion of the modified EGC in ED.

Similarly, with the same number of SU antenna at PFA of 0.1, the PD values obtained for the three techniques are also presented in Fig. 5. At SNR of 10 dB, PD values of 0.8945, 0.8426 and 0.3126 were obtained for EEMACSS, CMACSS and MANCSS, respectively, while at SNR of 16 dB, PD values of 0.9783, 0.9278 and 0.3667 were obtained, respectively, for EEMACSS, CMACSS and MANCSS. The results obtained reveal that at all the PFA considered, EEMACSS gives a better performance with higher detection rate and this is due to ED with a modified EGC used in the proposed technique that reduces the loss in signal strength of PU signal. Also, PD increases as PFA increases but at the expense of poor spectrum management. Fig. 5 depicts PD against SNR for EEMACSS, CMACSS and MANCSS with different PFAs at PU antenna of 2. At PFA of 0.01 and SNR of 10 dB, PD values of 0.5450, 0.5122 and 0.2699 were obtained for EEMACSS, CMACSS and MANCSS, respectively. Similarly, at PFA of 0.1, the PD values obtained at 10 dB were 0.6167, 0.5785 and 0.3138 for EEMACSS, CMACSS and MANCSS, respectively. The PD values obtained for SU antenna of four and two are tabulated in Table I and Table II, respectively.

TABLE I: PD VALUES FOR EEMACSS, CMACSS AND MANCSS WITH FOUR SU ANTENNAS AT DIFFERENT PFAS AND SNR

SNR	EEMACSS		CMACSS		MANCSS	
	PFA 0.01	PFA 0.1	PFA 0.01	PFA 0.1	PFA 0.01	PFA 0.1
0	0.1428	0.1436	0.1451	0.1449	0.0158	0.0154
4	0.6822	0.7661	0.6292	0.7091	0.1925	0.2216
8	0.7608	0.8592	0.7128	0.8049	0.2534	0.2922
12	0.8092	0.9158	0.7624	0.8629	0.2840	0.3293
16	0.8614	0.9783	0.8211	0.9278	0.3199	0.3667
20	0.8787	0.9978	0.8379	0.9488	0.3289	0.3783

TABLE II: PD VALUES FOR EEMACSS, CMACSS AND MANCSS WITH TWO SU ANTENNAS AT DIFFERENT PFAS AND SNR

SNR	EEMACSS		CMACSS		MANCSS	
	PFA 0.01	PFA 0.1	PFA 0.01	PFA 0.1	PFA 0.01	PFA 0.1
0	0.0989	0.0978	0.0995	0.0997	0.0147	0.0158
4	0.4687	0.5276	0.4324	0.4851	0.1883	0.2148
8	0.5223	0.5920	0.4896	0.5528	0.2427	0.2950
12	0.5556	0.6295	0.5237	0.5922	0.2886	0.3380
16	0.5918	0.6725	0.5634	0.6386	0.3170	0.3712
20	0.6040	0.6837	0.5749	0.6517	0.3286	0.3812

The values of SE obtained for EEMACSS and CMACSS at different number of PU antenna are presented in Fig. 6. At SNR of 10 dB, the SE values obtained with SU antenna of four were 14.8009 and 13.5006 for EEMACSS and CMACSS, respectively as against 12.1959 and 11.1245 obtained with SU antenna of three. At the same SNR with SU antenna of 2, the SE values obtained for EEMACSS and CMACSS were 10.1633 and 9.2704, respectively. The results obtained reveal that at all antenna configurations, EEMACSS has higher SE values than CMACSS due to reduction in signaling overhead thereby increasing bandwidth efficiency. Also, SE increases as the SU antenna and SNR increase which justifies reason for achieving more bandwidth efficiency at higher PU signal strength. Fig. 7 depicts the SE versus SNR at different clusters and SU. The SE values obtained at SNR of 20 dB with SU antenna of 2, were 6.5118, 9.4605 and 11.8291 for clusters 3, 4 and 5, respectively, while 14.0521, 16.0619 and 17.2269 were the corresponding values with SU antenna of 4. The results obtained reveal that, SE increases as number of clusters increases which justified the reduction in signaling overhead as cluster increases. It has also been confirmed that, SE increases as number of SU increases and this is due to increase in throughput as signal strength increases. The SE values obtained at different SNRs were presented in Table III.

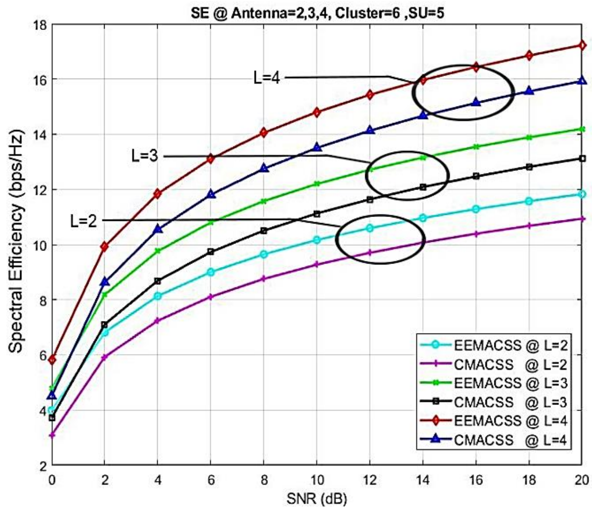

Fig. 6. Spectral Efficiency (SE) versus SNR for both EEMACSS and CMACSS at different SU antennas.

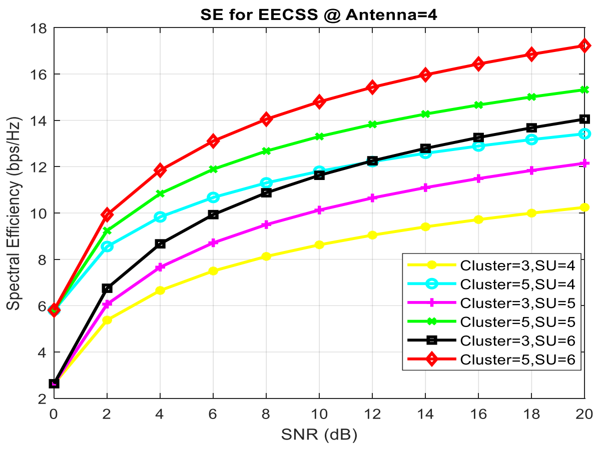

Fig. 7. Spectral Efficiency (SE) versus SNR for EEMACSS and CMACSS at different number of clusters and SU.

TABLE III: SE VALUES FOR EEMACSS AND CMACSS AT DIFFERENT SU ANTENNAS AND SNR

SNR	EEMACSS			CMACSS		
	Ant=2	Ant=3	Ant=4	Ant=2	Ant=3	Ant=4
0	3.99	4.78	5.80	3.09	3.71	4.50
4	8.13	9.76	11.84	7.24	8.69	10.54
8	9.65	11.58	14.05	8.75	10.50	12.75
12	10.59	12.71	15.43	9.70	11.64	14.13
16	11.28	13.54	16.43	10.39	12.47	15.13
20	11.82	14.20	17.23	10.94	13.12	15.93

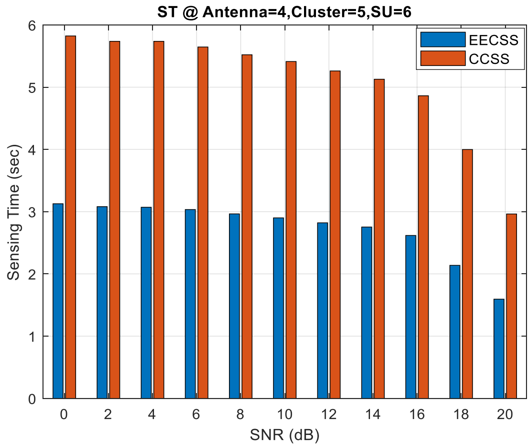

Fig. 8: Sensing Time (ST) versus SNR for EEMACSS and CMACSS at SU antenna of four.

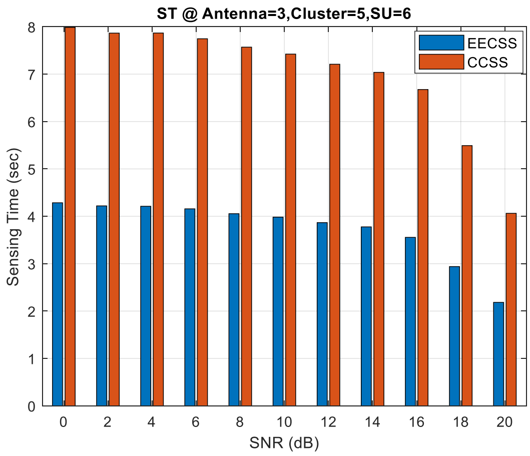

Fig. 9. Sensing Time (ST) versus SNR for EEMACSS and CMACSS at SU antenna of three.

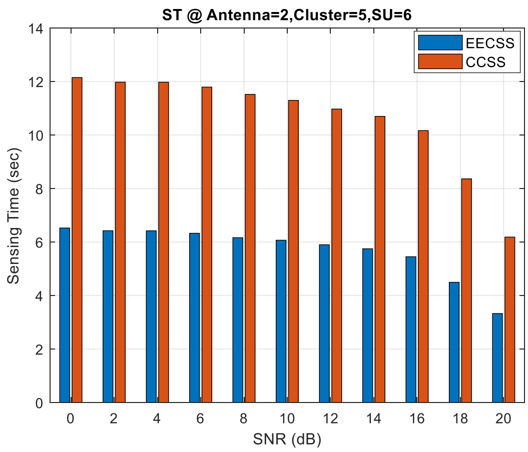

Fig. 10. Sensing Time (ST) versus SNR for EEMACSS and CMACSS at SU antenna of two.

Fig. 8 to Fig. 10 depict the Sensing Time (ST) versus SNR for the EEMACSS and CMACSS at different antenna configurations. Fig. 8 shows ST versus SNR for EEMACSS and CMACSS at PU antenna of 4. The results obtained reveal that at SNRs of 4, 8 and 16 dB, the ST obtained were 3.0707, 2.9000 and 2.6177 s, respectively, for the EEMACSS as against 5.7365, 5.4124 and 4.8622 s obtained for CMACSS. Fig. 9 presents ST versus SNR for both EEMACSS and CMACSS at SU antenna of three. ST values obtained for EEMACSS were 4.2112, 3.9824 and 3.5552 s at SNR of 4, 8 and 16 dB, respectively, as against 7.8675, 7.4230 and 6.6753 s for CMACSS. The ST results obtained at SU antenna of two with different SNRs for both EEMACSS and CMACSS are presented in Fig. 10. ST values of 6.4191, 6.0660 and 5.4500 s were obtained for EEMACSS at SNRs of 4, 8 and 16 dB, respectively, as against 11.9716, 11.2925 and 10.1638 for CMACSS.

The results obtained reveal that EEMACSS has lower ST values than CMACSS, this is due to hardware complexity reduction and cluster used in the proposed technique. Also, the results obtained reveal that ST increases as SU antenna and SNR reduce. This is due to the fact that the SU makes decision at a faster rate at higher signal strength. Fig. 11 shows the ST versus SNR at different clusters with SU antenna of 4. It has been confirmed that the ST decreases as cluster increases, due to reduction in signaling overhead as cluster increases. The results obtained in this paper is in agreement with IEEE 802.22 standard on CR. The ST values obtained at different antenna is tabulated in Table IV.

TABLE IV: ST VALUES FOR EEMACSS AND CMACSS AT DIFFERENT SU ANTENNAS AND SNR

SNR	EEMACSS			CMACSS		
	Ant=2	Ant=3	Ant=4	Ant=2	Ant=3	Ant=4
0	6.52	4.29	3.13	12.15	7.99	5.82
4	6.42	4.21	3.07	11.97	7.87	5.74
8	6.16	4.05	2.96	11.52	7.57	5.52
12	5.90	3.87	2.82	10.97	7.21	5.26
16	5.45	3.56	2.62	10.13	6.68	4.86
20	3.33	2.18	1.59	6.18	4.06	2.96

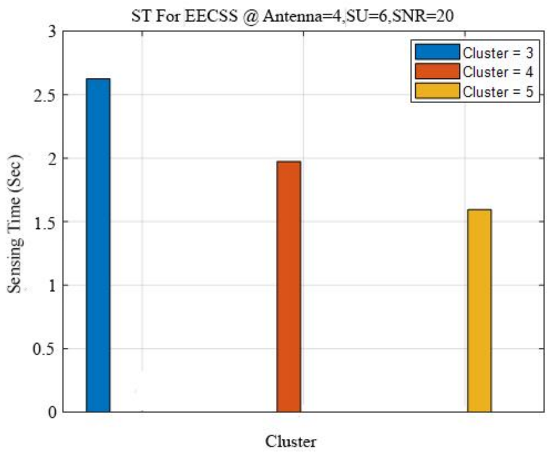

Fig. 11. Sensing Time (ST) versus SNR for EEMACSS and CMACSS at different cluster with SU antenna of 4.

VI. Conclusion

In this paper, a cluster-based EEMACSS for PU detection in a CR network has been proposed using ED with a modified EGC. The existing ED with EGC has been modified using single RF chain, MF to carry out local sensing at different configurations. The SU selection has been carried out based on the set threshold before carrying out local sensing to reduce hardware complexity. Mathematical expression of PFA for the proposed technique has been derived using X^2 distribution to set the decision threshold in determining the PD at local sensing. The local sensing results obtained at different SUs are combined at the cluster using majority fusion rule to determine the sensing results at each cluster. The sensing results from each cluster are then combined using OR fusion rule to determine the global sensing results. The proposed technique has been simulated and evaluated using PD, SE and ST. The results obtained reveal that the proposed EEMACSS gives better performance than each of the CMACSS and MANCSS due to lower ST, higher PD and SE values. The better performance of the proposed technique is due to the SU selection, ED with modified EGC and cluster used that reduce the hardware complexity and signaling overhead. The study reveals the hardware complexity and signaling overhead reduction in the proposed technique. The EEMACSS proposed can be used in communication system for signal detection in a 5G CR technology.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Samson I. Ojo conducted the research while Zachaeus K. Adeyemo supervised the process and adding technical inputs. Damilare O. Akande and Ayobami O. Fawole assisted in paper preparation.

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