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Enhancement of spectrum sensing technique with energy harvesting for cognitive radio network

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ABSTRACT

Spectrum sensing (SS) is cognitive radio's (CR's) fundamental and essential mechanism to locate idle spectrum. Multipath effects in wireless channels, on the other hand, reduce CR's sensing accuracy, resulting in a significant risk of missing data. Optimal spectrum sensing technique with energy harvesting (OSSTEH) used to solve this problem suffers from poor performance due to only one primary user (PU) branch used. Hence, in this paper, an enhanced SS with energy harvesting technique is proposed using Maximal Ratio Combiner (MRC). The multiple copies of the PU signal were received using 'N' number of secondary users (SU) antennas and divided into two equal fractions. The first fraction was used for spectrum sensing, while the latter was used for energy harvesting. The first set of SU antennas received a PU signal, which was combined using MRC, and the output of the combiner was used as an input to the energy detector to calculate the received signal's energy. To assess the existence or absence of the PU signal, the acquired energy was compared to the threshold limit. The enhanced technique was evaluated using the probability of detection and signal strength compared with conventional OSSTEH. The enhanced technique gave a high detection rate with an increase in charging rate than the conventional OSSTEH.

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1. INTRODUCTION

The spectrum scarcity problem in wireless communication is increasing daily due to the more bandwidth required to support many applications in various economic sectors of every nation. To serve ever-increasing customers, the frequency ranges acceptable for commercial applications are limited. The International Telecommunication Union (ITU) divides the frequencies into bands for different uses, hence radio spectrum allocation is now based on a fixed spectrum access paradigm. The license holder, known as the primary user (PU), has exclusive rights to use its spectrum, meaning no one else may use it. This protects license holders against interference [1], [2]. However, many parts of the approved radio spectrum are underused by licensed users, owing to the fact that many parts of the licensed spectrum are not utilised for extended periods of time. The conventional fixed spectrum strategy is wasteful and no longer possible because the number of users and their data rates function with time. The most common proposal in solving the problem of spectrum scarcity is to allow an unlicensed user to exploit the unused spectrum using cognitive radio (CR) technology [3], [4]. CR is a method that lets unlicensed users (secondary) to utilize the licensed (primary) spectrum's accessible sections without interfering with the primary users (PUs). In addition, CR is a technique that improves spectrum usage efficiency through dynamic spectrum access and provides a solution to the problem of spectral congestion through opportunistic usage of a spectrum that PUs does not heavily occupy. Primary user (PU) and secondary user (SU) are the two users in CR (SU). SU is an unlicensed user who uses the allotted spectrum only while PU is idle, whereas PU is a licensed user who has the authority to utilize the assigned spectrum [5]-[8]. The four-core operation in CR includes spectrum sensing (SS), spectrum decision (SD), spectrum analysis (SA) and data transmission (DT). SS, which is the method through which SU senses the allocated spectrum to assess the existence of PU and identify vacant spectrum holes, is the most important of these four key processes in the CR network [2], [9]. To make the most of the unoccupied spectrum and ensure the best possible protection for the primary transmission, SUs must conduct SS on a regular basis and decide on the availability of idle spectrum. However, battery replacement or recharging can prolong the life of SUs to some amount. However, such approaches are frequently expensive and, in certain situations, require awkward or even impossible processes [10], [11].

Energy harvesting (EH) is a new technology aimed at energy-constrained communication systems. Renewable energy sources recharge the battery, allowing the CR to work indefinitely without requiring external power cords or battery repairs. Therefore, incorporating EH in the CR network enables continuous spectrum sensing, greatly enhancing spectrum utilization and energy efficiency [12]. EH in wireless networks extracts energy from the ambient environment, such as wind, solar and radio frequency (RF) signals. Recently, EH from RF signals has been proposed to enhance SS and DT in CR networks [13], [14]. However, CR's sensing accuracy and EH depend on multipath propagation [15], [16]. Due to blockage in the terrestrial environment, multipath propagation describes a process in which a sent signal propagates in many copies. The effect of this process is a fluctuation of the PU signal, which could be so severe and resulting to a low signal below the sensitivity of SU. This effect causes poor signal reception, making PU difficult to sense [17]-[19]. If SU is unable to detect PU due to an obstruction, the likelihood of interference to the PU rises. Hence, hidden primary user problem that causes interference to PU and reduced RF power need to be mitigated [20]-[23]. Diversity combining technique (DCT) combined the multiple copies of the received signal, increasing signal strength [9]. Among the DCTs, maximal ratio combiner (MRC) gave better performance than other techniques due to combining the system's nature. Therefore, MRC was adopted in this paper to combine the multiple copies of PU signals before performing SS and EH. Energy detector (ED) that measures the energy of the PU signal within a pre-defined bandwidth and compared with a set threshold was adopted due to low implementation cost and computational complexities.

Spectrum sensing with energy harvesting for a CR network has been the subject of a number of previous studies. Zhang *et al*. [15], For EH-based CR, a simultaneous optimization of energy harvesting and spectrum sensing was proposed. The sensing and energy harvesting durations were optimized using dynamic time-slot to formulate optimization problems. Closed-form expression of SU's capacity was derived by considering the time duration for both spectrum sensing and energy harvesting. SU's capacity was then used to measure the performance of the optimized technique. Results obtained revealed that SU's capacity was maximized compared with conventional energy harvesting cognitive radio. However, the technique suffers from poor detection and charging rates due to only one PU branch being implemented in the system. Also, joint optimization of SS and transmit power in EH-CR sensor networks was presented in [24] to address the problem of energy constraint in energy harvesting cognitive radio networks. Using Markov decision process (MDP), resource allocation problems were formulated based on the channel occupation and sensing imperfection using Markov decision process (MDP). The given issues were handled utilizing the optimal sensing transmission (OST) strategy, which specifies the amount of time assigned for SS and the power level to be utilized for transmission. The technique was evaluated using battery discharging rates at a specific throughput. The result obtained revealed that the technique maximized sensing time while minimising power consumption but suffers from poor detection and charging rates due to only one PU branch being considered.

Furthermore, Gao *et al*. [13], a CR network with energy-harvesting based on primary and secondary user signals was proposed to solve the problem of energy constraint and the probability of false alarm resulting in poor spectrum management. Multi-objective optimization problem (MOP) was formulated based on detection rate, false alarm probability (FAP) and power consumption. The MOP was addressed by converting a multi-objective optimization problem into a single-objective problem by choosing one objective function as the main objective function and converting the other objective functions into constraints constrained by a certain amount of tolerance. Detection rate was chosen as the main objective function, while other functions such as probability of false alarm (PFA) and power consumption were used as constraints. Results of the paper revealed that the technique maximized detection rate and minimized PFA and power consumption compared with conventional energy harvesting cognitive radio. However, the technique suffers from poor detection rates at low PFA and signal to noise ratio (SNR) due to only one PU branch used. Energy harvesting with adaptive transmit power for cognitive radio network is proposed in [25] to address the problem of energy constraint in a cognitive radio network using radio frequency energy harvesting and adaptive power transmission (APT).

Channel state information (CSI) and secondary user (SU) transmitting power were adjusted based on channel gain, a CSI function using APT. According to the Author, SU uses low power to transmit the signal if the channel gain obtained is very high. However, if the channel gain is meagre, SU uses high energy to compensate for the loss due to inadequate channel conditions to maximize the system throughput. RF energy harvesting using a power splitter was used at the SU to scavenge energy at the PU signal. The harvested energy was used to recharge batteries and used for SU transmission. Closed-form expression of packet error probability (PEP) was derived and the results obtained showed that the technique was able to solve the problem of energy constraint in a CR network but suffers from poor detection rate with high PEP due to only one PU branch used in the system.

However, some of the existing works on energy harvesting based CR suffer from poor detection and low charging rates due to only one PU branch implemented. Therefore, in this paper, an enhancement of optimal spectrum sensing technique for energy harvesting enables cognitive radio network using maximal ratio combiner and antenna switching (AS) energy harvesting technique at the SU node. The contributions of this paper are as shown: i) A new sensing technique with improved detection and charging rates compared to the conventional sensing technique has been proposed. Improvement in detection rate increases PU protection and spectrum usage efficiency, while improvement in charging rate reduces energy constrained in CR, thereby eliminating periodic battery replacements; ii) Mathematical expression for the estimation of PFA for the new sensing technique has been derived and this can be used in setting a threshold for the proposed technique.

The remainder of the paper is structured as: the proposed enhanced spectrum sensing technique with energy harvesting is presented in section 2. In this section, the mathematical expression of PFA for the proposed technique was derived and used to set the decision threshold. Also, the mathematical expressions for PD and signal strength were derived to evaluate the performance of the enhanced technique. Section 3 presents the simulation results with performance comparison and section 4 concludes the paper.

2. PROPOSED SPECTRUM SENSING TECHNIQUE WITH ENERGY HARVESTING IN A COGNITIVE RADIO NETWORK

The proposed technique consists of PU antenna, Rayleigh channel, maximal ratio combiner (MRC), antenna switching (AS) and the SU antennas. The PU antenna served as the transmitter, the channel used was the Rayleigh, MRC was used for combining the reflected signals, AS was used for the spectrum sensing and energy harvesting with 4, 6, and 8 numbers of SU antenna used as the receiver. The randomly generated multiple copies of PU signal via a Rayleigh fading channel was received by 4, 6, and 8 SU antennas. For each pair of antennas employed, the SU antennas were divided into two parts, with the first fraction used for spectrum sensing and the second fraction used for energy harvesting. The PU signal received by the first set of SU antenna was combined with MRC, and the output of the combiner was sent into an energy detector (ED) to calculate the signal's energy, as shown in Figure 1. The obtained energy was compared with the set threshold to ascertain the presence or absence of the PU signal. If the acquired energy exceeds the set threshold, the spectrum is said to be occupied; otherwise, it is said to be idle. To reduce signal reflection, the PU signal received by another fraction of the SU antenna was combined using MRC, and the output of the combiner was used as an input to impedance matching (IM). The output of the IM was then sent into a voltage multiplier, which increased the voltage of the received signal, and a bridge rectifier, which rectified it. The direct current (DC) output of the rectifier was filtered using a capacitor and controlled with a voltage regulator, as shown in Figure 2. The regulator's DC output may now be utilized to recharge the battery for spectrum sensing and SU transmission. The output SNR of MRC $'\gamma_{MRC}'$ is given as:

$$\gamma_{MRC} = \frac{1}{wL}\left(\sum_{i=1}^{L} H \times S(i)\right)^2 \tag{1}$$

where: $S(i)$ is the signal power on each branch
L is the number of branches
w is the noise presents on each branch
H is the channel gain on individual branch
From (1), output of ED ‘E’ is given as

$$E = \sum_{n=1}^{N} |x(n)|^2 \tag{2}$$

where $x(n)$ is the PU signal equal to the output of MRC in this paper. Therefore, substituting (1) into Equation (2) gives:

$$E_{MRC} = \sum_{n=1}^{N} |\frac{1}{wL}(\sum_{i=1}^{L} H \times S(i))^2|^2 \quad (3)$$

as shown in (3) is the output of ED for the enhanced technique. Spectrum decision then uses the threshold to decide whether the spectrum is busy or idle and this threshold is given as;

$$E_{MRC} > \lambda \quad (4)$$

where: λ is the decision threshold.

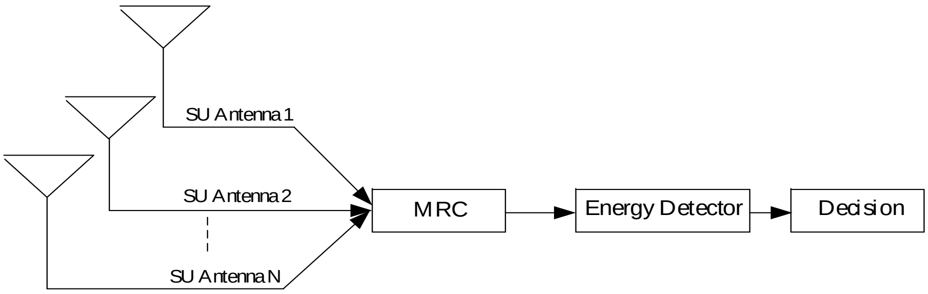

Figure 1. Block diagram of spectrum sensing for the enhanced technique

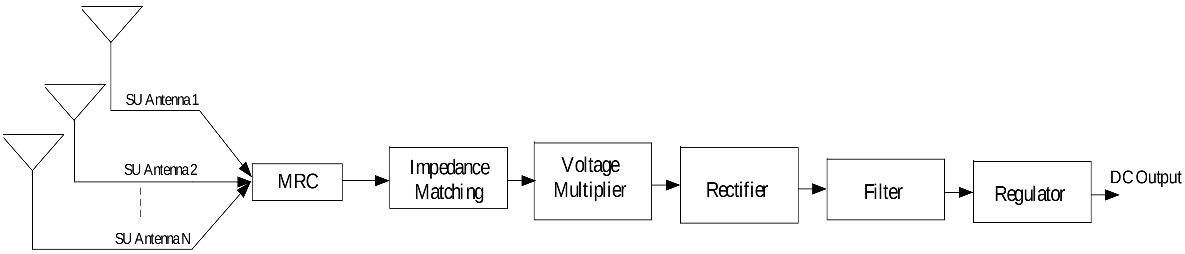

Figure 2. Block diagram of energy harvesting for the enhanced technique

2.1. Probability of false alarm for the enhanced technique

In this paper, the probability of false alarm (PFA) is the probability of falsely detecting the primary signal when the PU is silent in the scanned frequency band or the probability that exceeds a certain threshold when there is no signal. The PFA for the technique is derived as follows:

The total noise power 'w_{tot}' at the output of MRC is given by [26] as;

$$w_{tot} = \sum_{i=1}^{L} a_i w_i \quad (5)$$

where: a_i is the weight on each branch, w_i is the noise power on each branch

From Equation (3), the output of ED 'E_{MRC}' under H_0 hypothesis is expressed as;

$$E_{MRC/H_0} = \sum_{n=1}^{N} \mid \sum_{i=1}^{L} a_i(n) w_i(n) \mid^2 \quad (6)$$

Since E_{MRC/H_0} is a sum of a square, the test statistic distribution becomes a chi-square distribution. Using chi-square distribution, the distribution of the output of ED '$'f_{MRC/H_0}(\xi)'$ is given by [9] as;

$$f_{MRC/H_0}(\xi) = \frac{1}{(\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n))^{\frac{N}{2}} 2^{N/2}\Gamma(N/2)} \xi^{(N/2)-1} \, exp\left(-\frac{\xi}{2\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)}\right) \quad (7)$$

To obtain PFA, as shown in (7) is integrated with respect to the degree of freedom 'ξ'

$$PFA_{MRC} = \int_{\frac{\lambda}{2\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)}}^{\infty} f_{MRC/H_0}(\xi)\, d\xi \tag{8}$$

$$PFA_{MRC} = \frac{1}{\left(\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)\right)^{\frac{N}{2}} 2^{N/2}\Gamma(N/2)} \int_{\frac{\lambda}{2\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)}}^{\infty} \xi^{(N/2)-1}\, exp\left(-\frac{\xi}{2\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)}\right) d\xi \tag{9}$$

Integrating in (9) with respect to ξ using change of variable.

$$t = \frac{\xi}{2\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)} \tag{10}$$

$$\xi = 2\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)\, t \tag{11}$$

Differentiating both sides of (11) gives;

$$d\xi = \left(2\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)\right)dt \tag{12}$$

Then (10), (11) and (12) are substituted into (9) resulting to;

$$PFA_{MRC} = \frac{1}{\left(\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)\right)^{\frac{N}{2}} 2^{N/2}\Gamma(N/2)} \times \int_{\frac{\lambda}{2\sum_{n=1}^{N}\sum_{i=1}^{L} \sigma_i^2(n)}}^{\infty} \left(2\sum_{n=1}^{N}\sum_{i=1}^{L} \sigma_i^2(n)\right)^{(N/2)-1} t^{(N/2)-1} exp(-t)\, 2\left(\sum_{n=1}^{N}\sum_{i=1}^{L} \sigma_i^2(n)\right)dt \tag{13}$$

$$PFA_{MRC} = \frac{1}{\Gamma(N/2)} \int_{\frac{\lambda}{2\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)}}^{\infty} t^{(N/2)-1} \exp(-t)\, dt \tag{14}$$

Using incomplete gamma function $\Gamma(a,b) = \int_a^{\infty} t^{b-1} \exp(-t)dt$, in (14) gives;

$$PFA_{MRC} = \frac{\Gamma\left(\frac{\lambda}{2\sum_{n=1}^{N}\sum_{i=1}^{L} a_i(n)\sigma_i^2(n)}, N/2\right)}{\Gamma(N/2)} \tag{15}$$

where: Γ is the gamma function,
σ_w^2 is the noise variance.

2.2. Probability of detection

PD is the probability of making the right decision when PU is present. PD for the technique 'PD_{MRC}' is given as:

$$PD_{MRC} = \Pr(E_{MRC} > \lambda) \tag{16}$$

where: E_{MRC} is the output of energy detector
λ is the set threshold.

2.3. RF signal strength (RFSS)

The radio frequency signal strength (RFSS) is defined as the transmitter power output received by a reference antenna at a distance from the transmitting antenna. Therefore, the instantaneous strength of the received signal 'γ' in this work is given by [27] as;

$$\gamma = \frac{P_t H}{W} \tag{17}$$

where: P_t is the PU transmit power,
W is the noise present,
H is the channel gain

Using MRC, the signal strength for the enhanced technique 'γ_{MRC}' is given as;

$$\gamma_{MRC} = \frac{1}{wL}\left(\sum_{i=1}^{L}\gamma(i)\right)^2 \quad (18)$$

where: L is the number of PU branch.
w is the noise present.
By substituting (17) into (18) gives;

$$\gamma_{MRC} = \frac{1}{wL}\left(\sum_{i=1}^{L}\frac{P_t(i)H(i)}{W(i)}\right)^2 \quad (19)$$

Therefore, in (19) is the signal strength for the enhanced technique.

3. SIMULATION RESULTS

In this section, the results obtained were presented and discussed extensively. The PD and signal strength (SGS) were the metrics used to evaluate the performance of the enhanced spectrum sensing technique with energy harvesting (ESSTEH) cognitive radio network (CRN) by comparing with the technique proposed in [24] denoted as OSSTEH. The PD and SGS results were as presented in the following subsections.

3.1. Probability of detection at different propagation paths

Figures 3 to 6 present the PD versus SNR for the ESSTEH and OSSTEH at different constellation sizes and a different number of SU antenna (L). Figure 3 depicts PD versus SNR for the ESSTEH and OSSTEH at L=2 over Rayleigh fading channel. The PD values obtained at SNR of 8 dB with 4-QAM modulation scheme were 0.7611 and 0.5722 for the ESSTEH and OSSTEH, respectively, while at 16-QAM modulation scheme, the corresponding PD values obtained were 0.6066 and 0.4981 for ESSTEH and OSSTEH, respectively. The results obtained revealed that the enhanced technique gave a higher detection rate than the conventional technique and this is due to MRC that improves signal strength at the SU. Also, the results obtained showed that PD reduces as the constellation size of the modulation increases for the two techniques. This is because a signal with a small constellation size is robust in the channel compared with the signal with a larger constellation size though at the expense of a low transmission rate.

The PD versus SNR for ESSTEH and OSSTEH at L=3 over Rayleigh fading channel is presented in Figure 4. At SNR of 8 dB, the PD values obtained using the 4-QAM modulation scheme were 0.8995 and 0.6776 for ESSTEH and OSSTEH, respectively, while 0.7169 and 0.588 were the corresponding PD values obtained at the 16-QAM modulation scheme. Also, Figure 5 depicts PD versus SNR for ESSTEH and OSSTEH at L=4 over Rayleigh fading channel. At SNR of 8 dB using 4-QAM modulation scheme, PD values of 0.9894 and 0.7439 were obtained for ESSTEH and OSSTEH, respectively, while the corresponding PD values obtained using 16-QAM modulation scheme were 0.7886 and 0.6475. It can be deduced from the results obtained that the detection rate increases as the number of SU antennas increases. The result is due to an increase in signal strength as the SU antenna increases. Also, for the two techniques, PD increases as SNR increases, and this is due to an increase in detection rate as the signal transmitting power increases. However, at all the scenarios considered, ESSTEH gave a better performance with the highest detection rate when compared with the OSSTEH, and this is due to MRC that combined the received signal at the SU before applying energy detector (ED).

3.2. Signal strength results at different number of secondary user (SU) antenna

Figures 6, 7 and 8 present the signal strength (SGS) versus SNR for ESSTEH and OSSTEH at a different number of SU antenna (L) and constellation size of the modulation. Fig. 6 depicts SGS versus SNR for ESSTEH and OSSTEH at L=2 over Rayleigh fading channel. The SGS values obtained at SNR of 8 dB with 4-QAM modulation scheme were 6.0972 and 4.8295 dB for ESSTEH and OSSTEH, respectively, while at 16-QAM modulation scheme, the corresponding SGS values obtained were 4.3552 and 3.1560 dB for the ESSTEH and OSSTEH, respectively. The results obtained revealed that the enhanced technique has higher signal strength than the conventional technique and this is due to MRC used in the enhanced technique that improves signal strength at the SU. Also, the results obtained showed that the SGS reduces as the constellation size of the modulation increases for the two techniques. This is because a signal with a small constellation size is more robust in the channel than the signal with a larger constellation size though at the expense of a low transmission rate.

The SGS versus SNR for ESSTEH and OSSTEH at L=3 over Rayleigh fading channel is presented in Figure 7. At SNR of 8 dB, the SGS values obtained using the 4-QAM modulation scheme were 7.2058 and

5.708 dB for ESSTEH and OSSTEH, respectively, while 5.1470 and 3.7298 dB were the corresponding SGS values obtained at the 32-QAM modulation scheme. Also, Fig. 8 depicts SGS versus SNR for ESSTEH and OSSTEH at L = 4 over Rayleigh fading channel. At SNR of 8 dB using the 4-QAM modulation scheme, the SGS values of 7.9263 and 6.2783 dB were obtained for ESSTEH and OSSTEH, respectively, while the corresponding SGS values obtained using 32-QAM modulation scheme were 5.6617 and 4.1028 dB. The results revealed that signal strength increases as the number of SU antennas increases, which justifies the system's better charging rate at a higher number of SU antennas.

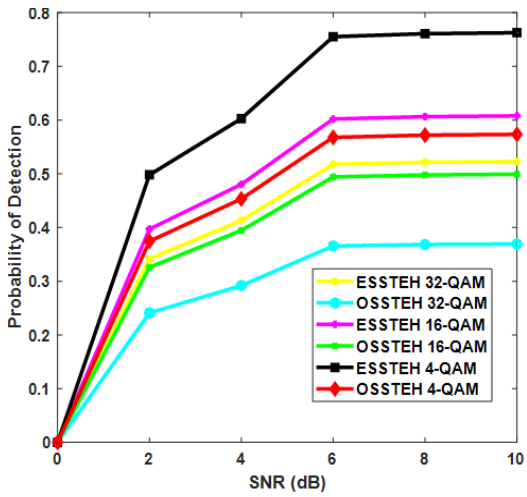

Figure 3. Probability of detection (PD) versus SNR for the ESSTEH and OSSTEH at L=2 over Rayleigh fading channel

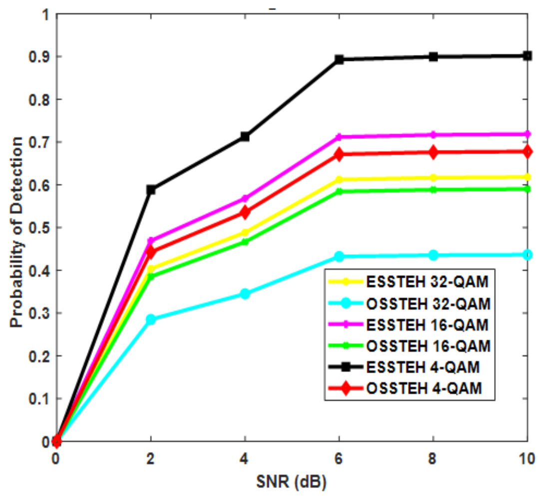

Figure 4. Probability of detection (PD) versus SNR for the ESSTEH and OSSTEH at L=3 over Rayleigh fading channel

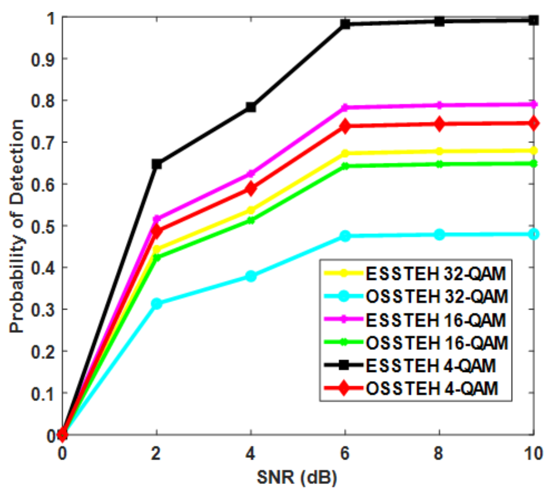

Figure 5. Probability of detection (PD) versus SNR for the ESSTEH and OSSTEH at L=4 overRayleigh fading channel

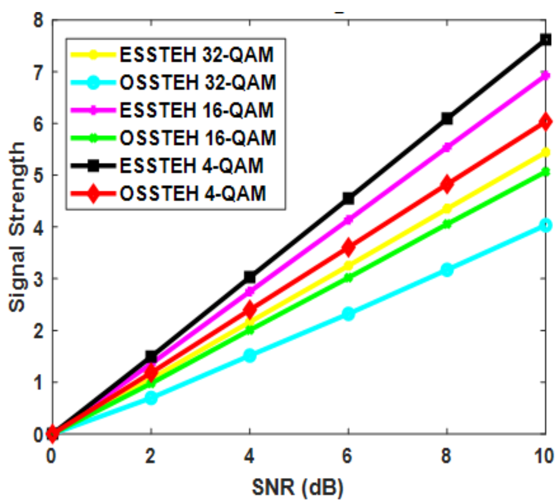

Figure 6. Signal strength (SGS) versus SNR for the ESSTEH and OSSTEH at L=2 with different constellation sizes over Rayleigh fading channel

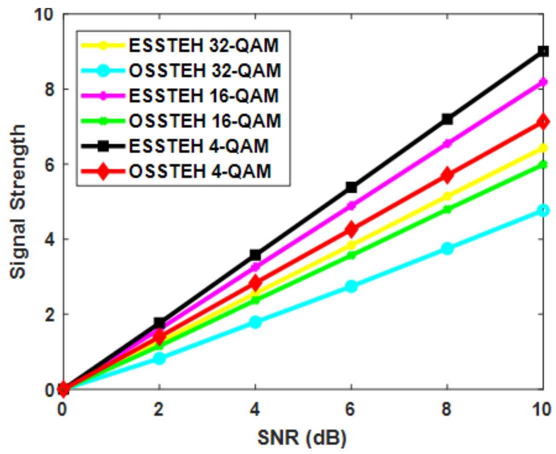

Figure 7. Signal Strength (SGS) versus SNR for the ESSTEH and OSSTEH at L=3 with different constellation sizes over Rayleigh fading channel

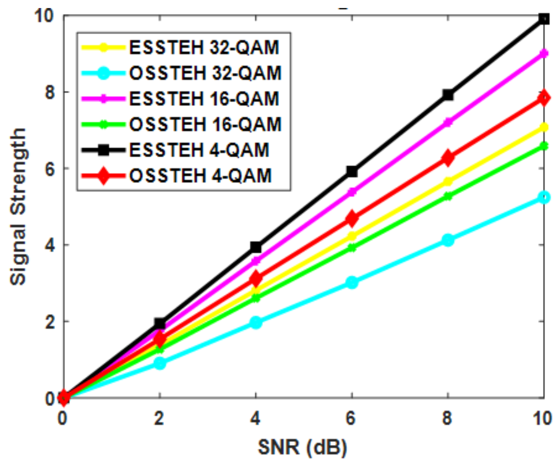

Figure 8. Signal Strength (SGS) versus SNR for the ESSTEH and OSSTEH at L=4 with different constellation sizes over Rayleigh fading channel

4. CONCLUSION

This paper proposed an enhanced spectrum sensing technique with energy harvesting (ESSTEH) for CRN over Rayleigh fading channel. Multiple SU antennas were used to receive multiple copies of PU signals. The SU antennas were separated into two portions, with the first being used for spectrum detection and the second being utilized for energy harvesting. The signal received by the first fraction of the SU antenna over the Rayleigh fading channel were combined using MRC before feeding it to the ED. The energy of the combined signal was obtained using ED and compared with the decision threshold to determine the presence or absence of PU. The mathematical expression of PFA for the enhanced technique was derived using the chi-square distribution. In the simulation process, the system model for the received PU signal at the SU was designed for the Rayleigh fading channel, while the noise was modelled as AWGN. The coefficient of the fading envelop was multiplied with the M-ary Quadrature Amplitude Modulation (M-QAM) signalling scheme with the addition of AWGN. The multiple PU signals were received at different SU antennal configurations of 4, 6 and 8 to investigate the effect of an increase in antennas on the enhanced technique. Probability of Detection (PD) and Signal Strength (SGS) values for the ESSTEH and OSSTEH were obtained at different SNRs with different constellation sizes. Performances of ESSTEH and OSSTEH have been evaluated at a different number of SU antennas with different SNRs using PD and SGS as performance metrics. The results revealed that ESSTEH showed better performance with a higher detection rate and signal strength. The better performance of the enhanced technique is due to MRC that combined the received signal before signal detection and energy harvesting was carried out. Also, for the two techniques, PD and SGS increase as SNR increases. This is due to an increase in PU signal strength as SNR increases. Consequently, the enhanced technique has effectively detected a PU signal over a Rayleigh fading channel with a better charging rate.

REFERENCES

[1] F. K. Ojo, D. O. Akande, A. I. Azeez, G. A. Oyeola, "Investigation of interference in cognitive radio using cooperative sensing techniques", *International Journal of Networks and Communications*, vol 5, no. 3, pp. 41-45, 2015, doi: 10.5923/j.ijnc.20150503.01

[2] K. Chang, "Spectrum sensing, detection and optimisation in cognitive radio for non-stationary primary user signals," PhD Thesis, Queensland University of Technology, 2012.

[3] M. A. Abdulsattar, "Energy detection technique for spectrum sensing in cognitive radio: a survey," *International journal of Computer Networks & Communications*, vol. 4, no. 5, pp. 223–242, Sep. 2012, doi: 10.5121/ijcnc.2012.4514.

[4] H. Wang, G. Noh, D. Kim, S. Kim, and D. Hong, "Advanced sensing techniques of energy detection in cognitive radios," *Journal of Communications and Networks*, vol. 12, no. 1, pp. 19–29, Feb. 2010, doi: 10.1109/JCN.2010.6388431.

[5] S. Hossain and I. Abdullah, "Hard decision based cooperative spectrum sensing over different," *International Journal of Advance Innovations, Thoughts & Ideas*, vol. 2, no. 3, pp. 1–12, 2013.

[6] N. Jain, "Interference cancellation and energy harvesting techniques for cooperative spectrum sharing cognitive radio systems Neha Jain," *Indraprastha Institute of Information Technology*, 2015.

[7] A. Celik and A. E. Kamal, "Green cooperative spectrum sensing and scheduling in heterogeneous cognitive radio networks," *IEEE Transactions on Cognitive Communications and Networking*, vol. 2, no. 3, pp. 238–248, Sep. 2016, doi: 10.1109/TCCN.2016.2608337.

[8] F. K. Ojo, D. O. Akande, and M. F. M. Salleh, "An overview of RF energy harvesting and information transmission in cooperative communication networks," *Telecommunication Systems*, vol. 70, no. 2, pp. 295–308, Feb. 2019, doi: 10.1007/s11235-018-0483-8.

[9] Z. K. Adeyemo, S. I. Ojo, R. O. Abolade, and O. B. Oladimeji, "Modification of a square-law combiner for detection in a cognitive radio network," *International Journal of Wireless and Microwave Technologies*, vol. 9, no. 2, pp. 32–45, Mar. 2019, doi: 10.5815/ijwmt.2019.02.04.

[10] F. K. Ojo and M. F. M. Salleh, "Throughput analysis of a hybridized power-time splitting based relaying protocol for wireless information and power transfer in cooperative networks." *IEEE Access*, vol. 6, no. 1, pp. 24137–24147, May 2018, doi: 10.1109/ACCESS.2018.2828121

[11] F. K. Ojo and M. F. M. Salleh, "Energy efficiency optimization for SWIPT-enabled cooperative relay networks in the presence of interfering transmitter." *IEEE Communications Letters*, vol. 23, no. 10, pp. 1806-1810, Oct. 2019, doi: 10.1109/LCOMM.2019.2929517

[12] O. Elnahas, M. Elsabrouty, O. Muta, and H. Furukawa, "Game theoretic approaches for cooperative spectrum sensing in energy-harvesting cognitive radio networks," *IEEE Access*, vol. 6, pp. 11086–11100, 2018, doi: 10.1109/ACCESS.2018.2810107.

[13] Y. Gao, H. He, Z. Deng, and X. Zhang, "Cognitive radio network with energy-harvesting based on primary and secondary user signals," *IEEE Access*, vol. 6, pp. 9081–9090, 2018, doi: 10.1109/ACCESS.2018.2797263.

[14] S. Shobana, R. Saravanan, and R. Muthaiah, "Matched filter based spectrum sensing on cognitive radio for OFDM WLANs," *International Journal of Engineering and Technology*, vol. 5, no. 1, pp. 142–146, 2013.

[15] S. Zhang, H. Zhao, A. S. Hafid, and S. Wang, "Joint optimization of energy harvesting and spectrum sensing for energy harvesting cognitive radio," in *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, Sep. 2016, vol. 0, pp. 1–5, doi: 10.1109/VTCFall.2016.7881058.

[16] M. Zheng, L. Chen, W. Liang, H. Yu, and J. Wu, "Energy-efficiency maximization for cooperative spectrum sensing in cognitive sensor networks," *IEEE Transactions on Green Communications and Networking*, vol. 1, no. 1, pp. 29–39, 2017, doi: 10.1109/TGCN.2016.2646819.

[17] S. I. Ojo, Z. K. Adeyemo, D. O. Akande, and A. O. Fawole, "Energy-efficient cluster-based cooperative spectrum sensing in a multiple antenna cognitive radio network," *International Journal of Electrical and Electronic Engineering and Telecommunications*, vol. 10, no. 3, pp. 176–185, 2021, doi: 10.18178/ijeetc.10.3.176-185.

[18] S. K. Pandey, "An anomaly detection technique-based intrusion detection system for wireless sensor network," *International Journal of Wireless and Mobile Computing*, vol. 17, no. 4, p. 323, 2019, doi: 10.1504/ijwmc.2019.10024335.

[19] J. Zhang, F. Ran, and D. Liu, "Maritime cognitive radio spectrum sensing based on multi-antenna cyclostationary feature detection," *International Journal of Electronics*, vol. 107, no. 7, pp. 1044–1062, Jul. 2020, doi: 10.1080/00207217.2019.1692373.

[20] R. Üstok, "Spectrum sensing techniques for cognitive radio systems with multiple antennas," PhD Thesis, Izmir Institute of Technology (Turkey), 2010.

[21] S. P. Singh and S. C. Sharma, "An improved cluster-based routing algorithm for energy optimization in wireless sensor networks," *International Journal of Wireless and Mobile Computing*, vol. 14, no. 1, pp. 82–89, 2018.

[22] R. Agarwal, N. Srivastava, and H. Katiyar, "Performance improvement of energy detector in cognitive radio using SECp diversity combining technique over fading channel," *International Journal of Wireless and Mobile Computing*, vol. 18, no. 2, p. 167, 2020, doi: 10.1504/IJWMC.2020.105706.

[23] S. I. Ojo, Z. K. Adeyemo, F. K. Ojo, A. A Adedeji, and F. A. Semire, "Enhancement of equal gain combiner for detection of spectrum hole in a cognitive radio system," *Universal Journal of Electrical and Electronic Engineering*, vol. 7, no. 5, pp. 289–298, Oct. 2020, doi: 10.13189/ujeee.2020.070503.

[24] F. Zhang, T. Jing, Y. Huo, and K. Jiang, "Joint optimization of spectrum sensing and transmit power in energy harvesting cognitive radio sensor networks," *The Computer Journal*, vol. 62, no. 2, pp. 215–230, Feb. 2019, doi: 10.1093/comjnl/bxy070.

[25] N. Ben Halima and H. Boujemâa, "Energy harvesting with adaptive transmit power for cognitive radio networks," *Telecommunication Systems*, vol. 72, no. 1, pp. 41–52, Sep. 2019, doi: 10.1007/s11235-019-00548-w.

[26] A. Goldsmith, "Wireless communication," in *2008 International Symposium on Telecommunications*, 2008, Frist edit., no. 142, pp. III–III, doi: 10.1109/ISTEL.2008.4651426.

[27] A. Z. Shaikh and T. Altaf, "Performance analysis of correlated multiple antenna spectrum sensing cognitive radio," *International Journal of Computer Applications*, vol. 50, no. 5, pp. 28–31, Jul. 2012, doi: 10.5120/7769-0848.

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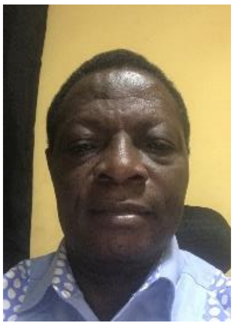

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