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Modification of a Square-Law Combiner for Detection in a Cognitive Radio Network

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Abstract

Spectrum sensing is of paramount importance in the Cognitive Radio Network (CRN) due to massive spread of wireless services. However, spectrum sensing in CRN is affected by multipath effects that make detection difficult. Square- Law Combining (SLC) technique, which is one of the methods previously used to address this problem, is associated with hardware complexity that results in long processing time. Hence, this paper aim to modify SLC technique for primary user detection in the CRN. The modified model consists of three Secondary User (SU) antennas which receive the faded signals through the Rayleigh fading channel. The received signals are combined using Switch Combiner (SC) at Radio Frequency (RF) stage. The selected signal passes through only one Energy Detector (ED) before making decision. The modified model is incorporated into simulation model which consists of Primary User (PU) transmitter that processes the randomly generated data through some signal processing techniques for transmission to the SU receiver. Probability of False Alarm (PFA) expression is derived for the modified Square-Law Combiner (mSLC) to set the thresholds at 6.64 and 9.14 for PFA of 0.01 and 0.02, respectively. The modified model is evaluated using Probability of Missing (PM), Probability of Detection (PD) and Processing Time (PT) to determine the performance. The results of the mSLC show that at SNR of 4 dB and PFA of 0.01, the values obtained for PD, PM, PT are 0.6575, 0.3530, 5.5540 s, respectively, as against the conventional SLC of 0.4000, 0.600, 6.2055 s, respectively. At SNR of 4 dB and PFA of 0.02, the values obtained for the mSLC are 0.7600, 0.3457, 6.1945 s for PD, PM and PT, respectively, as against 0.4000, 0.6000, 7.2197 s for conventional SLC. The results show that mSLC gives lower PM, higher PD and lower PT values when compared with conventional SLC.

Index Terms: Square Law Combining, Probability of Detection, Probability of Missing, Primary User, Secondary User, Cognitive Radio, Detector.

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1. Introduction

The massive spread of current wireless services and wireless communication evolution have given rise to a great need for more bandwidth with the purpose of offering various services such as radio broadcasting and internet services with high data rates. The accessible radio spectrum is becoming critically scarce and this is overcome by Cognitive Radio Networks (CRNs), introduced by Mitola in 1999 [1]. Cognitive Radio (CR) is a wireless communication in which a transceiver is intelligently detected communication channel in use and not in use. After which it is then instantly moved into idle channel while avoiding occupied ones [2, 14, 15]. It comprises two users namely: Primary User (PU) and Secondary User (SU). PU is the licensed user that owns the privileges to the assigned spectrum and SU is the unlicensed user which makes use of frequency spectrum only when PU is not active [3].

CR consists of four core operations namely: spectrum sensing, spectrum analysis, spectrum decision and data transmission. Spectrum sensing is the process by which SU senses the spectrum to detect the presence of PU and identifies empty spectrum spaces [4, 16]. It is an important requirement for the CR network in sensing the frequency band known as spectrum hole, in which a Secondary User can transmit without interfering with any Primary User. PU detection is found to be the most efficient way to detect spectrum holes [5]. The integrity of CR relies on the ability of the SU to restrict interference to PU and maintain a reliable quality of service for its own operations [4, 17, 18]. Spectrum analysis is the task in which SU analyses the detected spectrum space and determines whether the space is useful for the desired SU operation. Spectrum decision decides on which spectrum space to continue with communication and considers all the PU nodes within the SU network. Decision which is the instruction from the spectrum sensing, may instruct the nodes to remain on the particular channel, if PU is not active. It immediately moves to the next backup channel if PU is present.

Nomenclature

AWGN	Additive White Gaussian Noise
BPSK	Binary Phase Shift Keying
CR	Cognitive Radio
CRNs	Cognitive Radio Networks
ED	Energy Detector
EDs	Energy Detectors
SLC	Square Law Combiner
mSLC	modified Square Law Combiner
PD	Probability of Detection
PM	Probability of Missing
PT	Processing Time
PU	Primary User
SC	Switch Combiner
SU	Secondary User
SNR	Signal to Noise Ratio

In data transmission, SU transmits the data and adapts the transmission parameters such as frequency and modulation scheme to suit the propagation characteristics of different PU channels [4]. The sensing accuracy which is the ability of SU to sense PU without interference, depends on multipath propagation. Multipath propagation is a phenomenon that occurs when a transmitted signal propagates in multiple copies as a result of obstructions in terrestrial environment. The resulting effect of this phenomenon is fluctuation of the received signal which could be so severed as to produce a low signal below the sensitivity of the receiver. This causes poor reception of the signal and makes PU difficult to sense [6]. The difficulty in sensing PU is called hidden PU problem which is one of the challenges encountered during spectrum sensing in CR based systems. If SU cannot sense PU due to obstacles, then probability of interference to primary user increases. Hence, the hidden PU problem that causes interference to PU needs to be mitigated [7, 19]. Therefore, the Spectrum sensing is based on a well- known technique called signal detection and described as a method of identifying the presence of a signal in a noisy environment. The statistical effects of multipath phenomenon follow different fading distributions such as Nakagami-m distributions, welbull distribution, Rayleigh distribution and Rician distribution [8]. Rayleigh distribution where non-line of sight exists is used in this paper for modelling. The existing technique in solving multipath effects which affect sensing accuracy of the CRN such as Maximal Ratio Combiner (MRC), Square Law Combiner (SLC) are associated with hardware complexity due to many Energy Detectors (ED). Therefore, this paper modifies the conventional SLC to enhance the performance.

2. Detection Method

Energy Detection (ED) method is used to detect the presence or absence of signal using energy. ED is a common approach to spectrum sensing since it has a low computational complexity which is implemented in both time and frequency domains. The signal is detected by comparing the output of ED with the threshold which depends on the noise floor [20]. The block diagram of ED is shown in Fig 1. The input signal $x(t)$ is filtered with a Band Pass Filter (BPF) to select the specific band of frequency to which user wants to sense. This signal is squared by squaring device to obtain the energy of the received signal and the output signal is passed through integrator to determine the observation interval. The output of the integrator is compared with the predetermined threshold. If the values are above the threshold, then, PU is present otherwise PU is absent [9]. Output of energy detection, "E_{time}" is expressed by [7] as

$$E(t) = \sum_{t=0}^{t_1} |x(t)|^2 \quad (1)$$

where:
t_1 is the time interval to be sensed and
$x(t)$ is the transmitted signal by Primary User.

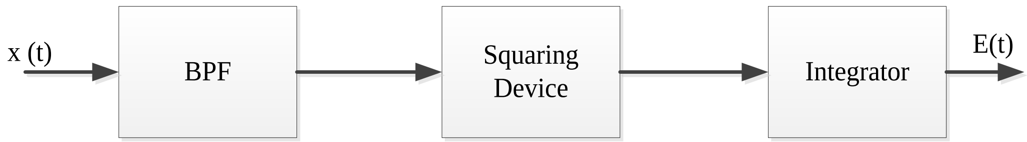

Fig.1. Block diagram of Energy detector [7]

3. Square Law Combining Technique

Square Law Combining (SLC) technique is a non-coherent combining technique which does not require channel knowledge. In this technique, ED is assigned to each antenna and output of each of the energy detectors are combined by selection combiner as shown in Fig. 2. Output of combiner is then used by CR to make a final decision whether PU signal is present or not. The operation of this technique is based on evaluating the energy of the received signal by each branch [10]. Output signal of SLC with each of the detectors (E_{SLC}) is given by [11] as

$$E_{SLC} = \sum_{k=1}^{N} |x(k)|^2 \quad (2)$$

where:
N is the symbol length to be sensed and
$x(k)$ is the transmitted signal by PU

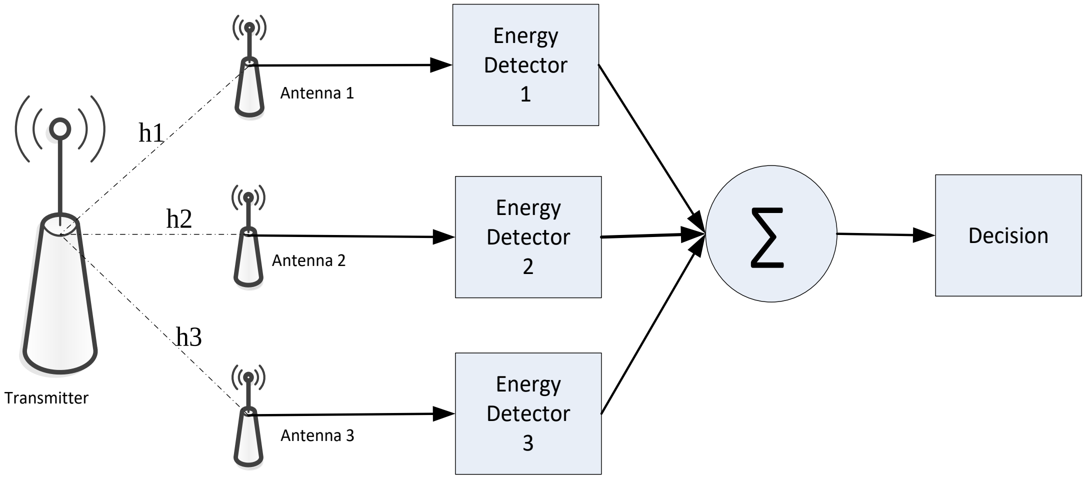

Fig.2. Square Law Combining technique with three ED

4. Switch Combiner (SC)

Switch Combiner (SC) is a type of combiner which searches through the diversity branches to find the one that has a Signal to Noise Ratio (SNR) exceeding a specified threshold. This branch is selected and used until the SNR drops below the threshold and thereby selecting another branch which has a Signal to Noise Ratio exceeding the threshold. This technique makes use of only one detector and there is no need of co-phasing since only one branch output is used at a time [2, 21]. The output SNR of the combiner 'γ' is given by [13] as

$$\gamma = \{\gamma_1 \dots \dots \gamma_l > \mathrm{T}\} \tag{3}$$

where:
γ_l is the received SNR per bit of the l^{th} branch at any instant and
T is switching threshold.

5. Related Work

In [22] performance analysis of Primary User (PU) detection in a multiple antenna CR is carried out to solve problem of interference caused by Secondary User to Primary User in CR system using Equal Gain Combining method. This method comprises ten receiving antennas, a combiner and only one Energy Detector. Each antenna receives PU signal which is randomly generated data, the received signal from each antenna is then multiplied with the product of the conjugate of the channel gain and inverse of its absolute value. The output data is then applied to only one Energy Detector (ED) to obtain the energy of received signals. Output of ED is then compared with the decision threshold to make a decision on whether PU exists or not. The result of this work shows that, this method provides diversity gain in detection performance but it requires perfect channel knowledge which makes it difficult to set threshold. Also, in [23] multiple detectors based analytical performance of spectrum sensing is carried out to solve interference caused by SU to PU in CR system using

Maximal Ratio Combining technique. In this paper, CR receives data from each antenna and multiplies them with the conjugate of each channel gain. The multiplied data is then summed and applied to an Energy Detector (ED). Output of ED is then compared with the decision threshold to make decision on whether spectrum is busy or idle. The result of this work shows that, this method provides some gain by having a very high probability of detection but difficult to implement in spectrum sensing system as it requires perfect channel knowledge. The existing works suffer from hardware complexity which makes the sensing time to be very high and perfect channel knowledge that resulted into difficult in setting threshold for the system. Due to these shortcomings, this paper therefore, develops a technique that requires no Channel State Information (CSI) and reduces complexity.

6. Methodology

The existing SLC modelled by [10] is modified by replacing several EDs with only one ED. Closed form expression for PFA for the modified model is derived and used to set decision threshold. Simulations using Matrix Laboratory (version 7.4) simulation software is used to investigate the performance of this model. Performance of the model is evaluated using Processing Time (ST), Probability of Detection (PD) and Probability of missing (PM).

6.1 Modification of Square Law Combining Technique

Modification of SLC model is carried out by replacing three EDs in the conventional SLC model with only one ED as shown in Fig 3. In this modified model, the transmitted signal from PU over a Rayleigh fading channel is received by three SU antennas. Switch combiner searches through these signals and selects the one that is above the set threshold. Output of switch combiner is applied to only one ED as shown in Fig 3 and h_1, h_2, h_3 are the Rayleigh fading channels. Output of ED is then compared with decision threshold of 6.64 and 9.14 at PFA of 0.01 and 0.02, respectively, to make a decision on whether PU signal exists or not. If the output of ED is greater than the set threshold, then PU signal is present, otherwise PU signal is absent.

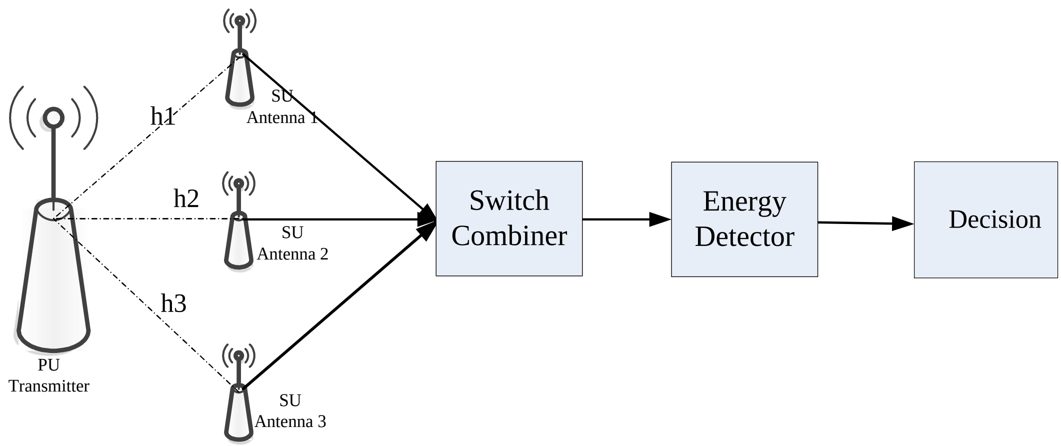

Fig.3. Modified Square Law Combining technique using only one ED

Output of ED for the modified model E_{mSLC} is given as

$$E_{mSLC} = \sum_{n=1}^{N} |S(n)|^2 \tag{4}$$

where :
E_{mSLC} is the output of ED for the modified model
N is the symbol length to be sensed
$S(n)$ is the transmitted signal by the Primary User.
Spectrum decision uses threshold value to make a decision whether the spectrum is busy or idle and this is in accordance with equation (5)

$$E_{MSLC} > \lambda \tag{5}$$

where:
λ is the decision threshold.

6.2 Probability of False Alarm

Probability of False Alarm (PFA) for the modified model is derived as follows:
Output of ED (E_{mSLC}) under H_0 hypothesis is expressed as

$$E_{mSLC} = \sum_{n=1}^{N} |w(n)|^2 \tag{6}$$

where:
N is the symbol length
$w(n)$ is the Additive White Gaussian Noise (AWGN) with zero mean and variance σ_w^2. Using chi-square distribution, the distribution of the output of ED '$f_{EmSLC}(\xi)$' is given by [7] as

$$\mathrm{f}_{EMSLC}(\xi) = \frac{1}{\left[\sqrt{\sum_{W=1}^{N}\sigma_W^2}\right]^N 2^{N/2}\Gamma(N/2)} \xi^{(N/2)-1} \; exp - \left(\frac{\xi}{2\sum_{W=1}^{N}\sigma_W^2}\right) \tag{7}$$

Therefore, the output of ED is integrated to obtain PFA.

$$PFA_{mSLC} = \int_{\frac{\lambda}{2\sum_{W=1}^{N}\sigma_W^2}}^{\infty} \mathrm{f}_{EMSC}(\xi)\, d\xi \tag{8}$$

$$PFA_{mSLC} = \frac{1}{\left[\sqrt{\sum_{W=1}^{N}\sigma_W^2}\right]^N 2^{N/2}\Gamma(N/2)} \int_{\frac{\lambda}{2\sum_{W=1}^{N}\sigma_W^2}}^{\infty} \xi^{(N/2)-1} \; exp - \left(\frac{\xi}{2\sum_{W=1}^{N}\sigma_W^2}\right) d\xi \tag{9}$$

$$PFA_{mSLC} = \frac{1}{\Gamma(N/2)} \int_{\frac{\lambda}{2\sum_{W=1}^{N}\sigma_W^2}}^{\infty} t^{(N/2)-1} \exp(-t)\, dt \tag{10}$$

Using incomplete gamma function $\Gamma(\varepsilon, b) = \int_{\varepsilon}^{\infty} t^{b-1} \exp(-t) dt$
Equation (10) gives

$$PFA_{mSLC} = \frac{\Gamma\left(\frac{\lambda}{2\sum_{W=1}^{N}\sigma_W^2}, \; N/2\right)}{\Gamma(N/2)} \tag{11}$$

where:
Γ is the gamma function,
N is the symbol length
λ is the decision threshold
σ_w^2 is the noise variance.

Using $N = 10, \sigma_w^2 = 1$, the decision threshold (λ) for the PFA of 0.01 is obtained as $\lambda = 6.64$, the decision threshold (λ) for PFA of 0.02 is obtained as $\lambda = 9.14$

7. Simulation Model

The system model for this work consists of PU transmitter, the Rayleigh channel 'D', and the receiver. Data acquisition is from the random integer generator, which is available within the MATLAB simulation software. PU transmitter processes the randomly generated data for transmission, by converting the source data into bits, reshaping and modulating with BPSK signalling scheme at different trials. The Square-Root Raised Cosine (SRRC) filter is used at the transmitter to reduce the bandwidth of transmitted signal for suitable transmission over the channel without losing any information and improving the spectral efficiency. The received signals over the Rayleigh fading channel are combined at the RF stage using Switch Combiner (SC). SC searches through the signals and selects the one that is greater than 6.64 set threshold. The signal at the output of SC is then passed through the RF chain, Matched Filter (MF) for further processing and finally demodulated using BPSK demodulator after being gray decoded. Gray decoder decodes the received signal and the signal is applied to ED to compute the received energy and compares with the decision threshold. D_1, D_2 and D_3 in Figure 4 represent multiplicative distortions otherwise known as Rayleigh fading channel over different paths and N_1, N_2 and N_3 represent the AWGN present in the environment. The complete simulation model for this work is shown in Fig 4.

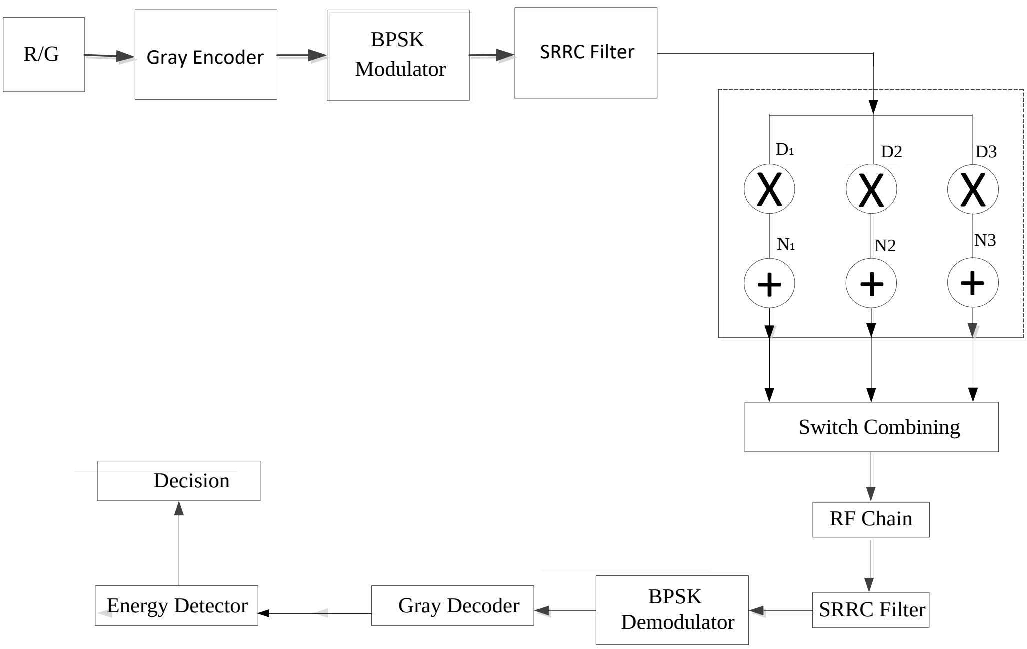

Fig.4. The system simulation model.

8. Results and Discussion

The values of PD, PM and PT obtained for both conventional and modified SLC are presented in Figs 5 to 11. Fig. 5 shows the Probability of Detection (PD) versus SNR for both conventional and the modified SLC at PFA of 0.01. The PD values obtained for the mSLC are 0.4000, 0.6575, 0.7940 at SNRs of 2, 4, 6 dB, respectively as against the conventional SLC with PD values of 0.2210, 0.4000, 0.6150 at SNRs of 2, 4, 6 dB respectively. Fig 6 shows the Probability of Missing (PM) versus SNR for both conventional and modified SLC at PFA of 0.01. At SNR of 2, 4, 6 dB, the PM values obtained for mSLC are 0.6000, 0.3530 and 0.2350 as against the conventional SLC of 0.7900, 0.6000 and 0.4600, respectively. Similarly, Fig 7 depicts the PD versus SNR for conventional and modified SLC at PFA of 0.02. It can be deduced that at SNR of 2, 4 and 6 dB, PD values obtained for mSLC are 0.4000, 0.7600 and 0.7900, respectively, as against 0.2200, 0.4000 and 0.6206 obtained for conventional SLC. Also, in Fig 8, at PFA of 0.02, PM values obtained for mSLC at SNR of 2, 4, 6 dB are 0.6000, 0.3450 and 0.2100, respectively, while 0.7800, 0.6000 and 0.3800 are respectively obtained for conventional SLC. The results obtained are also contained in Tables 1 and 2 for PFA of 0.01 and 0.02, respectively.

Fig 9 is Processing Time (PT) versus SNR for the modified and conventional SLC at PFA of 0.01. It is shown that at SNR of 2, 4 and 6 dB, the PT obtained for mSLC are 5.5374, 5.5540 and 5.6867 s respectively, as against 6.2050, 6.2055 and 6.2155 s respectively for conventional SLC. Fig 10 shows the Processing Time (PT) versus SNR for the modified and conventional SLC at PFA of 0.02. The results obtained show that at SNR of 2, 4 and 6 dB, the PT obtained are 6.1473, 6.1945 and 6.1961 s, respectively, for the mSLC as against 7.2009, 7.2197 and 7.3845 s for conventional SLC. The PT results obtained for both modified and conventional SLC at PFA of 0.01, 0.02 are presented in Table 3. The results obtained are justifiable in that only one Energy Detector (ED) is used in the modification and is used at RF stage which reduces the number of hardware to be used in the implementation, thereby reducing the processing time. The Probability of Detection (PD) are higher in mSLC than conventional SLC because of switching process of the model. The results obtained also show that, PD increases as SNR increases and this is due to ED that has poor performance at low SNR. The PD values obtained for both modified and conventional SLC are high at PFA of 0.02 compared with the PFA of 0.01 and leads to more wastage of spectrum. This paper is in agreement with the work of [7] where spectrum sensing technique for CR system with multiple antennas is carried out.

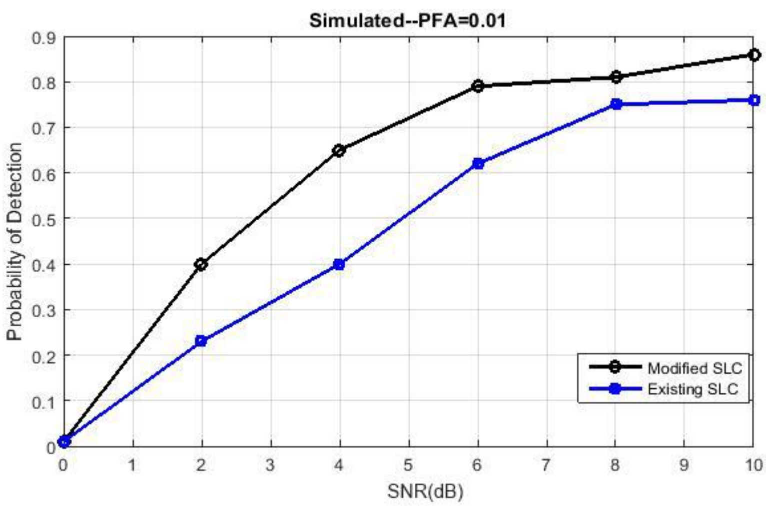

Fig.5. Probability of Detection versus SNR for conventional and modified SLC at PFA of 0.01.

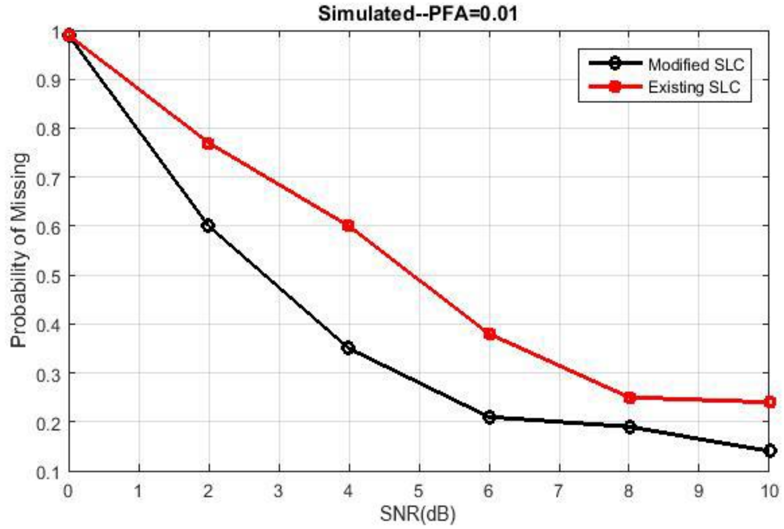

Fig.6. Probability of Missing versus SNR for conventional and modified SLC at PFA of 0.01.

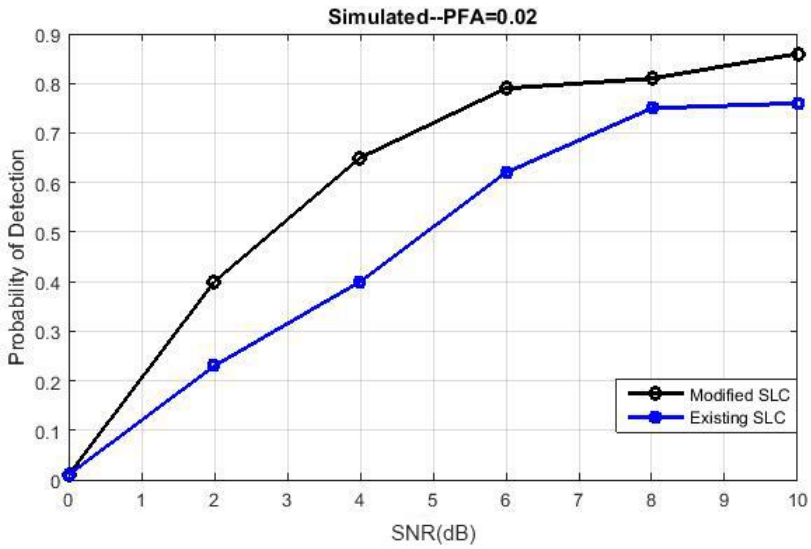

Fig.7. Probability of Detection versus SNR for conventional and modified SLC at PFA of 0.02.

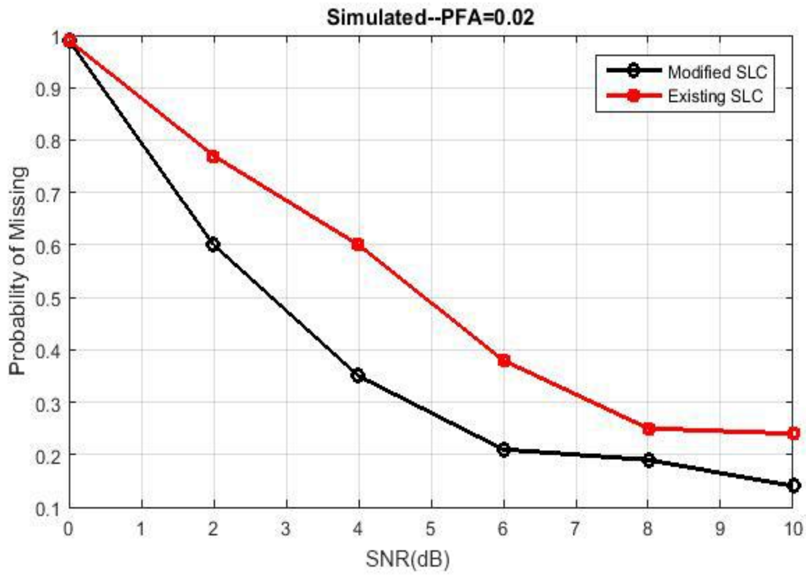

Fig.8. Probability of Missing versus SNR for conventional and modified SLC at PFA of 0.02.

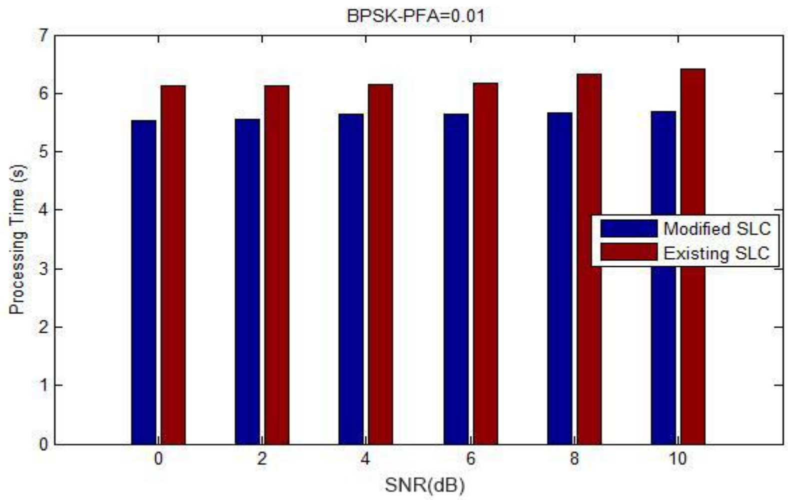

Fig.9. Processing time versus SNR for the modified and conventional SLC at PFA of 0.01

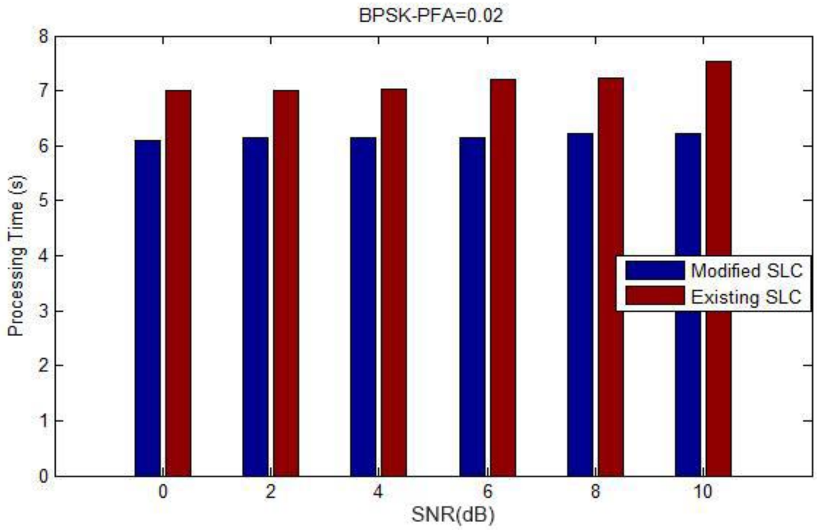

Fig.10. Processing time versus SNR for the modified and conventional SLC at PFA of 0.02

Table 1. Probability of Detection and Probability of Missing at PFA of 0.01

	Probability of detection		Probability of missing	
SNR	CSLC	MSLC	CSLC	MSLC
0	0. 0100	0. 0100	0. 9900	0. 9900
2	0. 2210	0. 4000	0. 7900	0. 6000
4	0. 4000	0. 6575	0. 600	0. 3530
6	0. 6150	0. 7940	0. 4600	0. 2350
8	0. 7500	0. 8152	0. 2600	0. 1940
10	0. 8700	0. 8800	0. 1300	0. 1450

Table 2. Probability of Detection and Probability of Missing at PFA of 0.02

	Probability of detection		Probability of missing	
SNR	CSLC	MSLC	CSLC	MSLC
0	0. 0000	0. 0200	0. 9800	0. 9800
2	0. 2200	0. 4000	0. 7800	0. 6000
4	0. 4000	0. 7600	0. 6000	0. 3450
6	0. 6206	0. 7900	0. 3800	0. 2100
8	0. 7500	0. 8150	0. 2500	0. 1954
10	0. 8500	0. 8750	0. 1960	0. 1450

Table 3. Processing Time at PFA of 0.01 and 0.02

	PFA = 0.01		PFA = 0.02	
SNR	CSLC	MSLC	CSLC	MSLC
0	6. 2000	5. 5360	7. 2002	6. 1340
2	6. 2050	5. 5374	7. 2009	6. 1473
4	6. 2055	5. 5540	7. 2197	6. 1945
6	6. 2155	5. 6867	7. 3845	6. 1961
8	6. 3921	5. 7100	8. 5419	6. 2276
10	6. 4650	5. 7345	8. 8416	6. 2285

9. Conclusions

In this paper, a modified Square-Law Combining (SLC) technique for Primary User detection in CR system has been developed. Mathematical expression for Probability of False Alarm (PFA) has been derived using chi-square distribution to set the threshold values to 6.64 and 9.14 at PFA of 0.01 and 0.02, respectively. The model has been simulated and evaluated using PD, PM and PT. The results show that the modified SLC performs better than the conventional SLC due to lower PM, higher PD and lower PT values. The performance of the modified SLC is as a result of combining nature of the signals before applying the ED. Modified SLC gives lower PT values due to only one ED used as against several EDs for the conventional SLC. Therefore, the modified SLC has been shown to have a better performance by having a higher PD, lower PM and lower PT than the conventional. The study shows the hardware complexity reduction and can be implemented in wireless communication system for signal detection.

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