Cognitive Radio: An emerging Technology for Effective Spectrum Utilization

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Abstract

Today, wireless communication deals with two main problems: spectrum scarcity and deployment delays. These problems are caused by the centralized manner and static in nature of frequency assignment. This scheme cannot adapt to the changing needs of spectrum by users from the military, governmental, and commercial purposes. Spectrum is no longer sufficiently available, because it has been assigned to primary users that own the privileges to their assigned spectrum. However, it is not used efficiently most of the time. In order to use the spectrum in an opportunistic manner and increase the spectrum availability, the unlicensed users can be allowed to utilize licensed bands of licensed users, without causing any interference with the assigned service. Cognitive radio (CR) is found to be an emerging key for efficient spectrum utilization. The technique of spectrum sharing among service providers to share the licensed spectrum of licensed service providers in a dynamic manner where the performance of the wireless network with opportunistic spectrum sharing techniques can be improved. There have been several research efforts on spectrum sharing in CR technologies in order to avoid spectrum scarcity and improve the spectrum utilization. This is considered as the main goal of our research work in a coordinated distributed manner and long-term spectrum assignment strategy.

Keywords: *Cognitive Radio, Spectrum Sharing, Spectrum Hole, Spectrum sensing, Frequency spectrum sharing.*

1. Introduction

Cognitive radio (CR) is an advanced technology in wireless communication systems, which allows the use of frequency spectrum efficiently. Proper utilization of frequency spectrum is possible by using dynamic spectrum allocation [1]. The CR users or the secondary users are allocated with the unused licensed spectrum available in the white space without causing interference to the licensed primary users. CR is one of the latest technology in which it has intelligence to automatically sense and learn the surroundings to accommodate the most appropriate user's requirements [2].

The major components of cognitive radio, which functions and adapts the transmission parameters according to the varying environment on a larger scale, it is an expansion of SDR.

This SDR-based wireless transceiver is the main component by means of the functions of signal transmission and reception. In addition, a wireless receiver is also sense the frequency spectrum used (observe the activity on the frequency spectrum). The spectrum analyzer uses measured signals to analyze the spectrum usage. This is to detect the signal signature from a PU and to locate spectrum holes for SU to access. The spectrum analyzer should take care that the transmission of a PU is not interfered with if an SU decides to access the spectrum. Learning and knowledge extraction use the information on spectrum usage to understand the behavior of RF environment of PU. A knowledge base of the spectrum access environment is built and preserve, which is consequently used to optimize and adjust the transmission parameters to get the desired objective under different restrictions. After the knowledge of the spectrum usage is available, the decision on accessing the spectrum has to be made. There are various techniques used to achieve a best solution. [3]

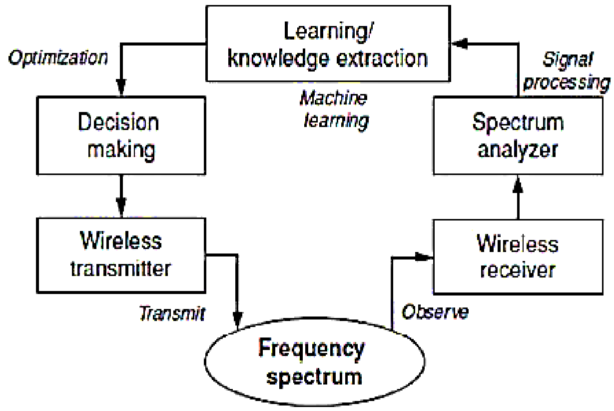

Fig.1 Components in a node of cognitive radio

Cognitive Radio Parameters and Objectives: -

Cognitive radio is able to interact with the environment and this can help to maintain the appropriate communication parameters in order to adjust as the dynamic radio spectrum. The parameters can be decided how communications can be occur with less interventions and large number of users can accommodate in radio spectrum. [2]

1.1 Transmission Parameters: -

The transmission parameters can decide to where the information can be transmitted and how they are communicated. These transmission parameters must be well defined before the fitness function is developed by the user. Table 1 shows the list of transmission parameters used.

Table 1: Transmission Parameters

Parameter Name	Discription
Transmit Power	Raw Transmission Power
Modulation Type	Type of Modulation Format
Modulation Level	No. of symbol used for a given scenario
Symbol rate	No. of symbol per second
Packet size	Size of the packet used for transmission

1.2 Environmental parameters: -

These parameters give knowledge to the cognitive radio system on the surrounding environment conditions. The sensed information through the surrounding helps the cognitive controller on making decisions. The three common environmental parameters used are bit error rate (BER), signal to noise ratio (SNR), noise power (N).

1.3 CR objectives: -

Table 2: Objectives of CR

Objective	Description	Fitness Function
Minimize bit error rate	Utilize spectrum with minimum errors	F_{min} BER = $\log_{10}(0.5) / \log_{10}(P_{be})$
Maximization of throughput	Maximize the user's data transmission	F_{max} T/Put = $\log_2(M) / \log_2(M_{max})$
Minimization of power consumption	Maximize efficiency by consuming less power.	F_{min} Power = P / P_{max}
Minimization of interference	Less no. of interferences	$F_{min-Int} = \{P+B+TDD- (P_{min}+B_{min}+1)\} / (P_{max}+B_{max}+RS_{max})$
Maximization of spectral efficiency	Frequency spectrum is used more efficiently	$F_{max-Spect} = 1- (M^* B_{min} *RS) / (B^* M_{max} * R_{Smax})$

Where,

Pbe represents the BER of modulation type being used.

M is modulation index of a single carrier and Mmax is the maximum modulation index.

P is average transmit power, Pmax is maximum available transmit power.

B= bandwidth required for single carrier, Bmin and Bmax is minimum and maximum bandwidth available, TDD is time division duplexing, RSmax=maximum Symbol rate.

Therefore optimization technique can be applied to optimize the spectral efficiency with the optimization the large no. of information can be transmitted with the limited bandwidth. [2]

2. Materials and Methods

2.1 Design Criteria:-

In cognitive radio network, secondary (unlicensed) users (SUs) are allowed to utilize the licensed spectrum when it is not used by the primary (licensed) users (PUs). Because of the dynamic nature of cognitive radio network, the activities of SUs such as "how long to sense" and "how long to transmit" significantly affect both the service quality of the cognitive radio networks and protection to PUs. To achieve higher spectrum utilization efficiency, the optimal sensing and data transmission length are investigated and found numerically.

In order to protect PUs, the interference brought by the activity of SU should be controlled into tolerable level. The traditional definition of spectrum efficiency is defined as the information rate that can be transmitted over a given bandwidth. Spectrum utilization efficiency is defined as, for specific licensed frequency band, the ratio of occupation time by the SU to the total free time.

To achieve higher spectrum utilization efficiency defined above, the sensing slot and the data transmission slot are required to be coordinated in a unit frame such that the licensed band occupation time by SU increases and at the same time the collided transmission time with the PUs decreases. [4]

Multiple trade-off problems exist in the frame structure optimization. From the SUs' perspective, the lower the probability of sensing errors occur, the more chances the channel can be reused when it is available, thus the higher the throughput of the SU could be achieved. Therefore, a tradeoff exists between the sensing length and throughput, which was formulated by using this frame structure of SUs. [4]

Compared with sensing length, transmission duration length also impacts the extent of interference between the PUs and the SU. Therefore the optimal transmission duration length should be also investigated for higher quality networks. [4]

The SU performs spectrum sensing to determine the status of each channel. The data transmission of the SU is activated subject to the spectrum sensing results based on the following two hypotheses for each channel

$$H_0 : y(n) = w(n); \quad (1)$$

$$H_1 : y(n) = h(n)\, s(n) + w(n); \quad (2)$$

Where y (n) is observed complex time series received at instant n, w(n) for all n = {1, 2, …, n}, represents an independent and identically distributed (i.i.d) circularly symmetric complex Gaussian (CSCG) with zero mean and N0 variance. Hypothesis H0 and H1 stand for the spectrum band detected are idle and occupied respectively. In (2), the vector h(n) typically represents the propagation channel between the corresponding PU and the SU and the signal s(n) for all n = {1, 2, …, n}, Ng denotes a standard scalar i.i.d random process and stands for the source signal to be detected.

Once the channels has been confirmed as idle, the SU is allowed to transmit on the channel and we assume (i) the SU is heavily loaded and always has data to transmit, (ii) the traffic loads of the PUs are exponentially distributed with the mean of the occupied and the idle durations denoted by α1 and α0 respectively.

In order to derive the spectrum utilization efficiency, which is defined as the ratio of occupation time by the SU to the total free time, the mean of both occupation time and collision time per frame should be calculated firstly. In practice, spectrum sensing is always imperfect and the sensing errors due to missed detection lead to interference between the SU and the PU where the channel is wrongly considered idle while the false alarm makes the SU keep silent even if the idle channel is available to SU.

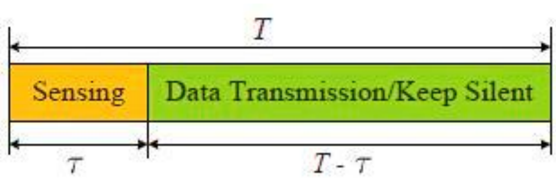

Fig. 2. A graphical structure of a typical frame structure of SU cognitive radio transmission.

Moreover, another type of spectrum sensing errors which is referred to as false alarm would not cause interference but will reduces the spectrum utilization efficiency of the licensed frequency band. Because we assume that the traffic loads of the PUs are exponentially distributed with the mean of the occupied and the idle durations denoted by α1 and α0 respectively in the condition that missed detection occurs, the percentage of transmission with collisions out of data transmission duration is given by

$$P_{ip} = \frac{\alpha_1}{T-\tau}\left(1 - \exp\left(-\frac{T-\tau}{\alpha_1}\right)\right)$$

Which is illustrated in Fig. 3 the SU performs energy detection for spectrum sensing and transmits data on the frequency bands based on the decision made during the sensing phase.

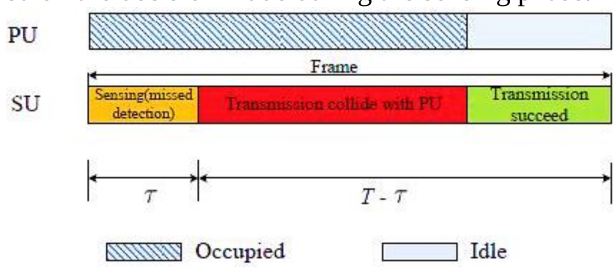

Fig. 3. A graphical illustration of a typical cognitive radio transmission with missed detection.

With any given sensing length, the probability of detection and false alarm for the channel under energy detection scheme are given by:

$$\mathscr{P}_d(\tau,\epsilon) = \mathcal{Q}\left(\left(\frac{\epsilon}{N_0} - \gamma - 1\right)\sqrt{\frac{\tau f_s}{2\gamma+1}}\right).$$

$$\mathscr{P}_{fa}(\tau,\epsilon) = \left(\left(\frac{\epsilon}{N_0} - 1\right)\sqrt{\tau f_s}\right).$$

Where ε denotes the decision threshold of the energy detector on the licensed channel, λ is received signal-to-noise ratio (SNR) from the PU at the secondary detector on the licensed channel and fs represents the sampling frequency, is the complementary distribution function of the standard Gaussian. To control the interference to PUs, target detection probability Pd should be guaranteed. [4]

2.2 Energy Detection: -

Spectrum sensing is the task of detecting holes (whitespaces) in frequency bands licensed to primary wireless networks, for opportunistic use by the secondary network. The decision upon the spectrum occupancy can be independently (non-cooperatively) made by each CR or can be reached by means of cooperation among multiple CRs. In centralized cooperative sensing, data collected by each cooperating CR (e.g., received samples) are sent via a reporting control channel to a fusion center (FC), in a process called data-fusion. The binary decisions made by the CRs are combined at the FC using binary arithmetic before the final decision is arrived. [5]

Two important parameters associated with the assessment of the spectrum sensing performance are the probability of detection, Pd, and the probability of false alarm, P_{fa}, which are defined according to

$$P_{\mathrm{d}} = \Pr\{\text{decision} = H_1 \mid H_1\} = \Pr\{T > \gamma \mid H_1\}$$
$$P_{\mathrm{fa}} = \Pr\{\text{decision} = H_1 \mid H_0\} = \Pr\{T > \gamma \mid H_0\},$$

Where $\Pr\{\cdot\}$ is the probability of a given event, T is the detection-dependent test statistic and γ is the decision threshold. The value of γ is chosen depending on the requirements for the spectrum sensing performance, which is typically evaluated through receiver operating characteristic (ROC) curves that show Pfa versus Pd as they vary with the decision threshold γ.

Eigenvalue-based detection: Among the existing spectrum sensing detection techniques, Eigenvalue-based schemes are receiving a lot of attention, mainly because they do not require prior information on the transmitted signal. In some eigenvalue-based schemes, the knowledge of noise variance is not needed either. In eigenvalue spectrum sensing, the test statistic is computed from the eigenvalues of the received signal covariance matrix. Although ED is not an exclusively eigenvalue-based detection technique, it can be implemented using eigenvalue information. [5]

Threshold value is an important factor to determine the performance of the detector. It has a great effect on the probability of detection and the probability of false alarm. However the energy detector design is simple, it has several limitations; such as it has a high false alarm probability due to the noise uncertainty, more samples are required to achieve acceptable performance, and it has a low performance when shot noise and fading channels are applied. The performance of the energy detector can be evaluated by three parameters and they are; the probability of detection, the probability of missed detection, and the probability of false alarm. The probability of detection is the number of the detected primary users (identified by the energy detector) divided by the total number of the primary users who are assumed to be present in the beginning. The probability of missed detection is the number of primary users that cannot be detected, divided by the total number of primary users who are assumed to be present in the beginning. The probability of false alarm is the number of the detected primary users divided by the total number of primary users who are assumed to be absent in the beginning. [6]

The performance of Energy detection is better in AWGN and also when K factor is high. It also increases line of sight performance for single as well as multi path reception. [6]

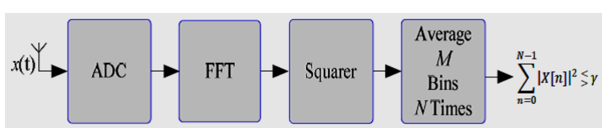

Fig.3 Block diagram of Energy Detector for CR

Still energy detection is badly affected by uncertainties in noise variance. Instead, by exploiting the second order periodicity inherent in most modulated signals cyclostationary detection can be used for reliable spectrum sensing. Cyclostationary approach can be combined with other detection techniques at low SNR. Frequency Shift filters were as the optimum time varying filter structures for estimation of cyclostationary signals. They consist of a bank of filters, each preceded by a frequency shifter that is tuned to a specific periodicity in the incoming cyclostationary signal. Hence FRESH filtering is also called polyperiodic filtering. [7]

Frequency Shift or FRESH filters are time varying filters which exploit the spectral coherence in cyclostationary signals to optimally estimate them. FRESH filter consists of many branches, each having a frequency shifter followed by a time invariant filter where each shift is equal to the cyclic frequency of the input signal. [7]

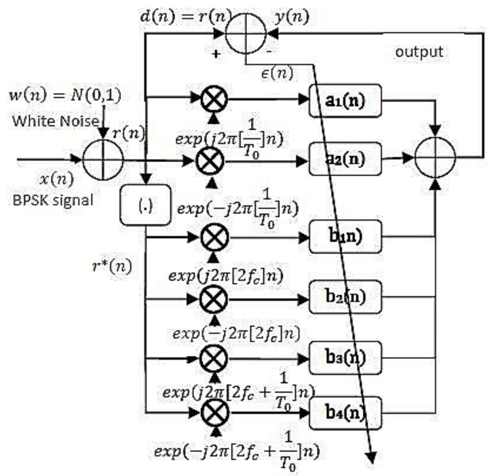

Fig.4 FRESH Filter structure

FRESH filter architecture gives better detection probability in the low SNR regime. It is also shown that the use of FRESH filters can improve the detection probability in cyclostationary spectrum sensing. [7]

2.3 ROC Curve: -

Spectrum sensing is a challenging task for cognitive radio. Energy detection is one of the popular spectrum sensing technique for cognitive radio. The probability of detection increases significantly when signal to noise ratio increases. It is also observed that the detection probability decreases when the bandwidth factor increases. Receiver characteristics (ROC) analysis for the signal detection theory to study the performance of the energy detector. ROC has been widely used in the signal detection theory due to the fact that it is an ideal technique to quantify the tradeoff between the probability of detection (Pd) and the probability of false alarm (Pfa). It is observed that the probability of detection is increased when false alarm probability is increased and probability of detection is decreased when the time bandwidth factor is increased.

ROC curves are used to plots of the probability of detection vs. the probability of false alarm. The probability of detection varies based on SNR, false alarm probability and various time bandwidth factors. SNR influences on the detection probability. When SNR increases, the detection probability increases. Again the detection probability varies depend on time bandwidth factor. If time bandwidth factor increases, the detection probability decreases. The false alarm probability also effects on detection probability. If false alarm increases, the detection probability increases. [8]

3. Results and Discussion

3.1 CR Model Simulation: -

Here, the CR module is simulated to analyze the spectrum utilization factor as per the proposed methodology as above. The CR module simulated includes 10 licensed PUs and 10 SUs. The method of modulation is BPSK. Total 10 channels are considered available for transmission. For better interference avoidance, the channel frames are interleaved with 16 bit interleaving data. The channels are encoded with 128 bit FFT and cyclic number is chosen to be 16. The In order to complete the task of spectrum sensing, a cognitive user must make a decision based on the output of the FRESH (Frequency Shift) filter as to whether the primary signal is present or not. The spectrum sensing is implanted using Eigen value based energy detection using FRESH filters. As stated earlier, using energy detection yields a highly unreliable test at low SNR due to noise uncertainty problem which may also fail to limit the false alarm rate. To counter this problem, we propose to measure the Conjugate Cyclic Autocorrelation function of the filter output and formulate a binary hypothesis test with a constant false alarm rate The number of sub carrier for SU transmission is same as that of available channels i.e. 10. 1000 Monte carlo events are selected for simulation period of 5 Hrs. The events can be selected more which will increase the accuracy of simulation but it also increases the simulation time and calculation complexity.

1. Simulation Graphs: The CR scenario is simulated using Matlab 2015a version, a powerful simulation tool. The following are the results displayed while simulations run cycle,

The original PU signal with 50% efficiency: -

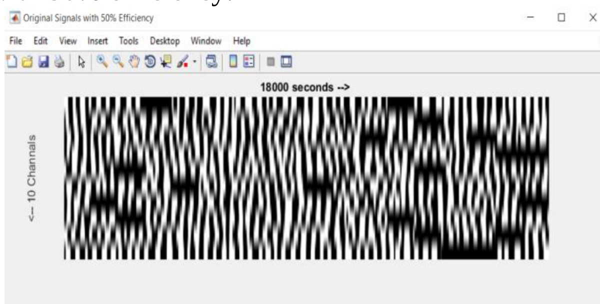

Fig.5 SU signal with data always ready to sent

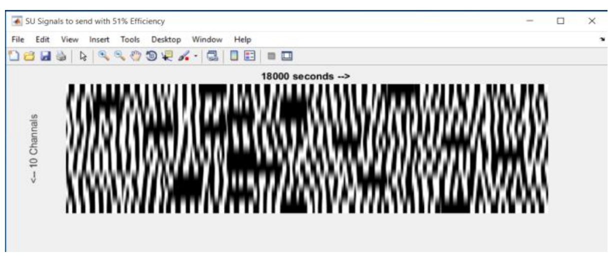

Fig. 6 spectrum utilization by Primary and Secondary Users

The above graph shows the spectrum utilization by Primary and Secondary Users. The white area indicates the utilization of spectrum for data usage. The black area indicates the spectrum hole as none of the user is utilizing the spectrum in that particular time-space region.

3.2 Observed Signal after Spectrum sensing: -

When CR concept is implemented and the spectrum is sensed using energy detection method, the following scenario occurs. The graph shows the area where SUs are successful to detect PU, and where SUs are not successful to detect presence of PUs. The graph also shows the Red area where there are chances of interference to PUs due to simultaneous transmission of PUs and SUs. This situation arises due to false detection by SUs. Apart from that, white region shows successful implementation of CR without any error. From the graph, almost 90% of spectrum is utilized by PUs and SUs for data transmission without any error. The same can be verified from combined CR transmission graph.

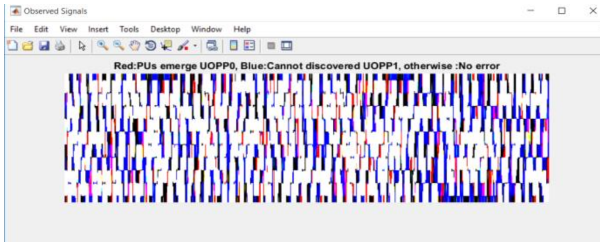

Fig.7 Combined CR transmission Signal

3.3 Spectrum Utilization For all 10 Channels by SUs: -

The following graph shows channel wise utilization factor after implementation of CR in the given environment. The utilization factor is calculated using formula, SUF = Occupation time by SU / Total free time. The time duration is considered as 300 instants of time for every channel. Each primary user is assigned a fixed channel as per fix spectrum assignment policy. Hence the simulation is considered for 10 channels. The graphical representation of spectrum utilization of each channel shows that Cognitive radio effectively utilizes the spectrum holes of every channel and transmits SU data. The time which is not utilized for SU data transmission is consumed by CR for spectrum sensing and maybe it is wasted due to collision avoidance by CR.

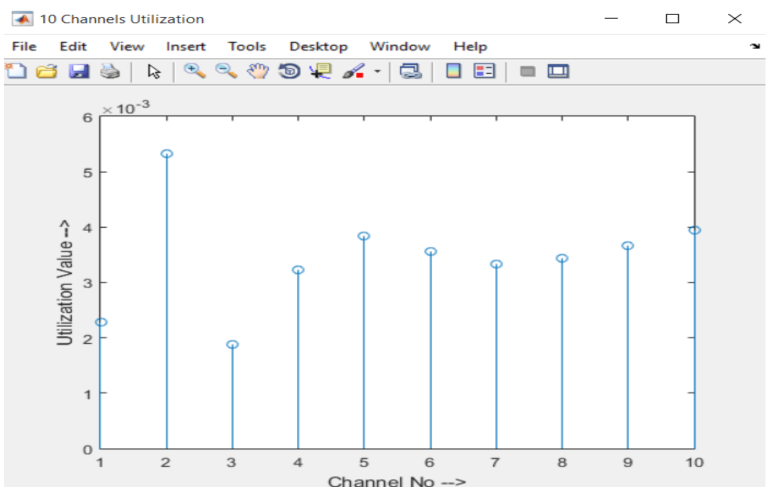

Fig. 8 Spectrum Utilization For all 10 Channels by SUs

3.4 Theoretical Spectrum sensing for deciding threshold:-

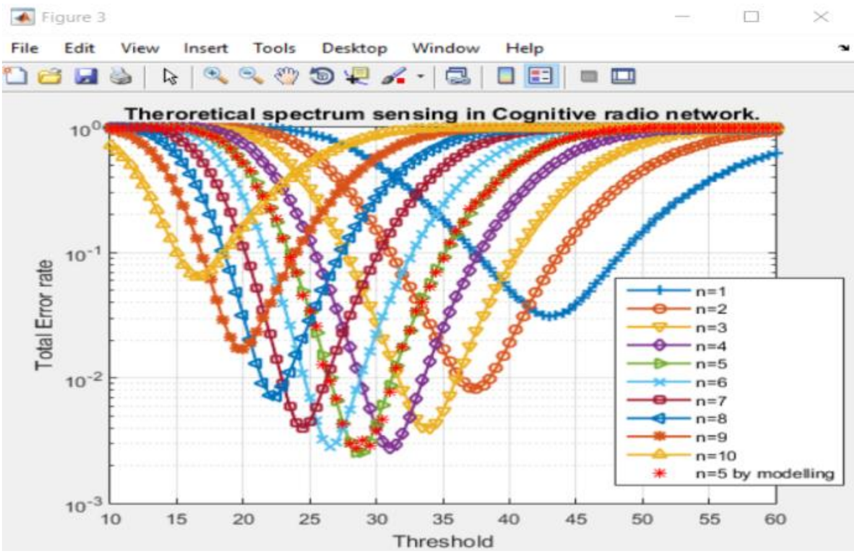

Fig. 9 Theoretical threshold value for energy detection method implemented for spectrum sensing

3.5 Theoretical Vs Achieved Spectrum sensing and Probability of False Alarms:-

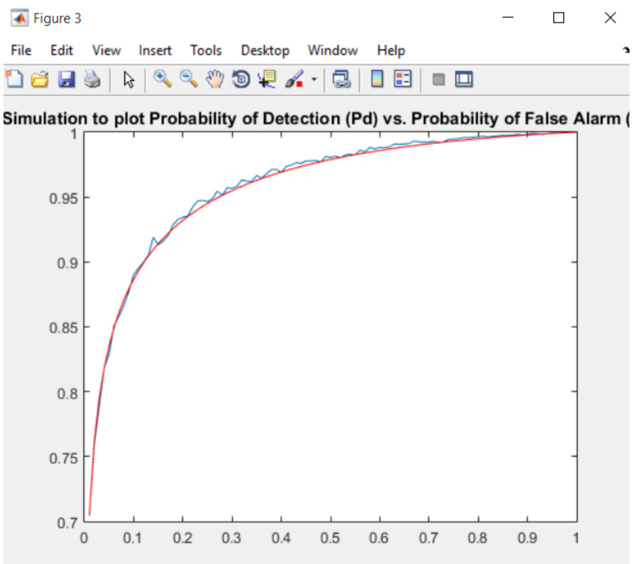

Fig. 10 Theoretical Vs Achieved Spectrum sensing and Probability of False Alarms

3.6 SNR for CR Simulation:-

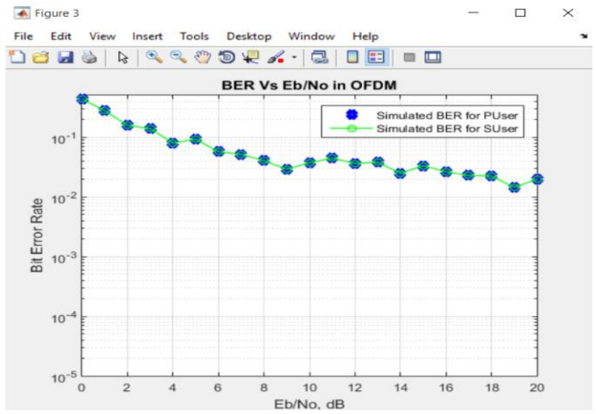

Fig. 11 Signal to Noise ration achieved during simulation

The above three graphs shows theoretical threshold value for energy detection method implemented for spectrum sensing. The first graph clearly indicates that the threshold is higher for low SNR value. As the SNR improves, the value of threshold can be reduced significantly. It means that, higher the value of SNR, greater the probability of detection. The second graph here indicates ROC curve for energy detection. It shows that probability of detection is higher for higher value of SNR and if false alarm probability increases, the detection probability also increases. The ROC curve is almost following the theoretical expected value of threshold calculated as per graphical representation in first graph. As shown by the graphs, the Max value of SNR is at 10^{-2} error rate. At this particular error rate, the threshold is at its max value. Hence for every simulation, SNR is approximated at value of 10-2 so that Pd can be at its max value. The same is confirmed by the simulation graphs.

3.7 Summary of Simulation Cycles:-

PU Efficiency	Utilization factor of SUs × 10^{-3}										Avg. Utilization factor	Total Occupancy by SUs	% Efficiency of CR
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**			
60%	6	3	2	4	3.5	3	4	3	5	3	0.0036	10.95	87
50%	3.7	2.5	2	4.9	3	4	2.5	3.5	3.5	3	0.0028	8.535	90
40%	3.5	4.5	3.5	5.5	5.5	4. 5	6.5	3.5	4	3	0.0044	13.2	87
30%	3.5	4	2	4.5	3.5	5.3	4.5	4.5	5	2.2	0.0039	11.7	89
20%	5.5	2	3.8	4	4.5	4.5	4	2	5.5	5	0.0041	12.24	89
10%	3.5	4	4	3	6	4	3.5	5	6	3.5	0.0042	12.75	90

4. Conclusion

The simulation of CR using MATLB has given exposure to the basic functionalities of CR and also helped to understand the implementation of CR using MATLAB.

The CR with BPSK modulation scheme is implemented to analyze the efficient spectrum utilization over conventional wireless communication scheme. The Spectrum sensing as one of the most critical issue of CR is tackled by implementing Cyclic Correlation filters in conjunction with traditional energy sensing algorithm. It helped to improve spectrum sensing ability even in low SNR environment. The CR is implemented with BPSK modulation scheme. The simulation is executed with blank space of minimum 30 seconds to maximum of 300 seconds. The original spectrum efficiency of PUs are varied from 10% to 60% and corresponding SUs transmission are observed. It is found that even if in worst spectrum hole of 300 seconds, the SUs utilize max 12 seconds in the slot and thus increases the efficiency of system almost up to 90% in most of the cases. The blank spot in transmission of PUs are effectively utilized by SUs and for all the cases, the SNR is always high up to 10-1 to 10-2. The Spectrum sensing and false alarm condition is also verified with theoretical spectrum sensing threshold. The practical spectrum sensing ability and probability of false alarm condition is within close proximity of ideal value as observed from graph.

The most important consideration is, how many wireless applications should be considered for the model. The application area is so vast that we have to restrict the model to certain few applications. Also, it has to be given a thought that which applications can have the agreement of Primary user and Secondary User. Whether to restrict the area of concern or to keep it wide such as building, Campus, Colony or city. Hence the basic CR with BPSK modulation is simulated in this phase. The simulation has proven that CR is powerful tool to improve spectrum utilization almost up to 90%.

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