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A modified energy detection based dynamic spectrum sharing technique and its real time implementation on wireless platform for cognitive radio networks

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Cognitive radio offers a flexible and efficient utilization of radio frequency resources by dynamic spectrum sharing as required in next gen (5G) architecture of wireless communication. The channel allocation time, probability of false alarm detection and spectral efficiency are the major performance parameters to characterize a spectrum sharing technique. This paper presents modified energy detection based dynamic channel allocation technique based on sensing the power spectral density of idle spectrum bands *i.e.* spectrum hole. Receiver operating characteristics (ROC) curves have been used to analyze the detector performance of sensing with respect to probability false alarm at different values of SNR. Allocation of unoccupied bands to the SUs has been done by coalition based cooperative game, which provides SUs with an incentive to cooperate. Based on their worth, SUs get payoffs which have been computed using Shapely values as a one-point solution. Vickrey–Clarke–Groves (VCG) auction mechanism has been used to allocate the spectrum resources fairly to each user. On the basis of allocation time, the present model for dynamic spectrum access appears to be more efficient as compared to the conventional opportunistic spectrum access model.

Keywords: Cognitive radio, Dynamic spectrum access, Spectrum sharing, WARP, Cooperative game, Shapley values, VCG auction

1 Introduction

Cognitive radio, a recent innovation by J. Mitola[1], has emerged as a promising solution to be focused for improved utilization of radio resources to cater the growing demand of diverse wireless applications in 5G scenario. The conventional static spectrum allocation policies have created considerable under-utilization of spectral bands in time, space and frequency domain. The idle period of a spectrum band referred to as white spaces or *spectrum holes*, offer great opportunity to share spectrum among licensed and unlicensed users to cater the spectrum scarcity. To ensure the rational, fair and economical usage of the spectrum, relevant government authorities all over the globe have issued spectrum allocation reforms policies which allow unlicensed or *secondary users* (SUs) to dynamically access the unused licensed spectrum bands, provided that they do not cause harmful interference to the licensed or *primary users* (PUs)[2]. The Department of Telecommunications (DoT), Govt. of India, has also notified the spectrum sharing rules, which allows the sharing of presently available spectrum and the additional frequency bands allocated in future. DoT guidelines for 5G trials across all available spectrum bands and is likely to allocate up to 400 MHz of radio waves for the purpose[3].

Conventionally, in wireless communication terminology, spectrum sharing is authorized utilization of the same span of frequencies by two or more user wireless applications on a non-exclusive basis in a defined sharing arrangement[4]. The original standard spectrum sharing architecture is Opportunistic Spectrum Access (OSA), wherein the PU and the SU have mutual exclusive access to the spectrum. The SU can access the spectrum only when PU is not using that portion of spectrum, which means that SU relies on sensing the spectrum to detect the presence or absence of available primary user signal on the frequency band. Although OSA has great potential to enhance the spectrum utilization to fullest, however the re-emergence of a PU signal may cause arbitrary disruption to SU and may result in highly unstable and unpredictable performance and poor quality of service (QoS) for SU's communication. Such limitations of OSA could be addressed by managing spectrum sharing between SUs and PUs dynamically using cognitive radios[5]. The limited available spectrum and the inefficient spectrum usage

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have brought in a new communication paradigm to exploit the existing wireless spectrum opportunistically and is referred to as Dynamic Spectrum Access (DSA) and cognitive radio networks (CRN)[6].

The CRN allows wireless communication system to rely on so-called cognitive cycle. The cognitive capability of CR *i.e.* ability to sense and identify the idle portions of the spectrum in time and space and re-configurability to adjust the software as per the result of spectrum sensing, are the key features to facilitate sharing of specific band of radio spectrum between licensed PUs with other opportunistic cognitive user or SUs without causing harmful interferences to PUs. In CRN, spectrum sharing[7] involves four steps as depicted in Fig. 1.

The first step of spectrum sharing is to sense the spectrum holes. Cognitive user (or SU) constantly detects the portions of spectrum, which are in use by PUs in time, space and frequency domain. Once the precise detection of spectrum holes is accomplished, the next step is to distribute or allocate the available band to SUs. An efficient spectrum access is the third key requirement to coordinate among SUs and PUs. The fourth step, spectrum handoff governs the working and switching of PU and the mobility of SUs to avoid latency or collision between them.

Classical spectrum sensing approaches are energy detection, matched filtering detection, and cyclostationary detection, where the spectrum sensing algorithms are based on the user's transmitter signal[8]. Such algorithms have the advantages of high technology maturity, low design difficulty, and easy realization. Matched filtering is a correlation based approach whereas in cyclostationary method considers cyclic features of the transmitter signal. *Energy detection* (ED) method relies on estimating the power of each frequency of the signal (Power Spectral Density, PSD) and results can be presented as periodogram or Welch periodogram. Among different methods reported in literature ED method is simple to realize hence most popular signal detection method in practical implementation.

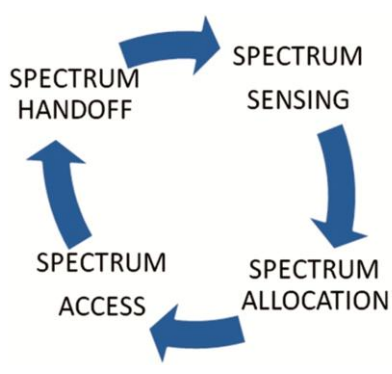

Fig. 1 — Spectrum Sharing Paradigm in CRN

A comprehensive overview on spectrum management needs to be considered to fulfill the next generation requirements of spectrum in cognitive radio wireless networks. The network architecture for spectrum sharing can be centralized or distributed. In *centralized networks*, a central entity controls the spectrum allocation and access procedure, accordingly a spectrum allocation map is constructed; whereas in *distributed* (de-centralized) networks, each node is responsible for spectrum allocation and access is based on local policies. On the basis of spectrum allocation behavior, the spectrum sharing approach can be non-cooperative or cooperative. The *non-cooperative* spectrum allocation is a ‘selfish’ approach, where the impact of one secondary node/user’s activity on other secondary nodes is not considered. In *cooperative* approach, each SU consider its own spectrum requirement, along with its interference and influence on other SUs present in the system network. The interference measurement of each secondary node/ user is shared among other nodes. This localized operation provides an effective balance between a centralized and a distributed architecture. Further on the basis of spectrum access, the system may follow overlay, underlay or hybrid approach[9]. In *overlay approach*, SU transmit with different power levels within spectrum holes in accordance with the power level of PU. The *underlay approach* allows PUs and SUs to transmit simultaneously. The SU transmits at lower power by enforcing a spectral mask so that the interference temperature by the SU is below the acceptable level of interference to PU. The *hybrid spectrum sharing* (HSS) is a sensing-based spectrum sharing approach where SU adapt the transmission power based on sensing the PU's transmit power. If the PU is detected to be absent, the SU can access the primary band with a higher transmit power; otherwise, it will transmit at a lower power. Numbers of HSS based studies are reported, exploiting cooperative multiband sensing[10-12], sensing time[13], reporting errors[14], and Dinkelbach's method based iterative power allocation algorithm[15] for energy-efficient spectrum sharing. An ergodic capacity of SU link under joint transmit and interference power constrain has also been used for sensing based spectrum sharing[16]. A low complexity algorithm based on graph-theory and mixed integer coding is proposed for underlay spectrum sharing paradigm[17].

Essential features of spectrum sharing are coexistence of PUs and SUs, fairness in spectrum access, optimum utilization of spectrum, low switching cost, realistic implementation and interference resolution mechanism. Accordingly various spectrum allocation approaches based on mathematical theories or microeconomics including Graph based, Auction based, and *Game Theory* based models have emerged[18]. In recent years, there has been a significant growth in research activities that use game theory[19] for analyzing communication networks as it provides a formal analytical framework with a set of mathematical tools to study the complex interactions among users/players. Thus we are equipped with various optimality criteria for spectrum sharing. In concordance with the spectrum allocation approaches, the game theoretical approach in-general can be modeled as a non-cooperative or cooperative in CRNs. The non-cooperative game theory, studies the strategic choices of the competing users who choose their own independent strategy to improve their own performance or utility. The cooperative game takes into account the interactions among the users, making the spectrum sharing more efficient and fair. Although, the payoff of non-cooperative game is lower than that of cooperative game model, however the spectrum utilization efficiency is higher in cooperative approach. For stable sharing, the game theory aims to reach steady state *i.e.* a stable point at which no player (*i.e.* users) can change their strategy; concept of '*Nash equilibrium'* is used in non-cooperative games whereas '*Core*' is solution concept for cooperative game. Fairness in allocation can be achieved using one of the 'one-point solutions' such as *Shapely values* that lie within the core[20,21]. Dynamic model with bounded rationality[22] and bandwidth auction[23] based non-cooperative game model have been reported for spectrum allocation.

A cooperative approach using stochastic geometry theory[24] has been used for spectrum sharing between cellular and ad-hoc networks, wherein the transmission capacity of the ad-hoc network and the average throughput of the cellular network are analyzed. A contract-based[25] hybrid approach is proposed for spectrum sharing, where SUs switch their transmission mode between underlay and overlay based on the second-order statistics of the primary links in a cooperative architecture. Saad *et al.*[26] have simulated a cooperative game theoretic model for joint spectrum sensing and access in CRNs. The game is modelled in partition form where SUs make individual distributed decisions to join or leave the coalition, while maximizing their utilities. Rajasekharan *et al.*[27] have simulated spectrum sharing in CRNs where SUs sense the spectrum cooperatively to access unoccupied spectrum bands and VCG auction mechanism is followed for fair allocation. For CR based communication paradigm, it is important to demonstrate the simulated model on a fully working over-the-air implementation testbeds. Testbed speed up the simulation and provide experimental validation of model in real time. Reports on implementation of spectrum sensing models employing different CR testbeds[28-31] offer significant contribution over just theoretical studies.

Based on this motivation, the paper presents a cooperative game theory based modified approach to address the spectrum sensing and allocation as a joint model for spectrum sharing in CRNs and its real time implementation on WARP to evaluate the performance in terms of spectral efficiency, channel allocation time and probability of false alarm.

2 Cooperative game based spectrum sharing approach

In communication networks, the spectrum sensing is a stage during which SUs attempt to understand the communication environment prior to the spectrum access stage when the SUs actually transmit their data, thus SUs are subjected to a trade-off between sensing and access when the SUs seek to improve both the aspects. Therefore, an overall joint framework on spectrum sensing and allocation as a cooperative game appears an achievable solution for efficient spectrum sharing in CRNs. A brief theoretical background of the spectrum sharing model used in present study is given in following sub-sections.

2.1 Spectrum sensing

The Neyman-Pearson (NP) criteria is being used to compare the log-likelihood ratio (LLR) with a predetermined threshold, for implementing the *energy detection technique* as shown in[8] :

$$\log \frac{(P(x_0, x_1, x_2 \ldots\ldots x_{(N-1)})|H_1)}{(P(x_0, x_1, x_2 \ldots\ldots x_{(N-1)})|H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda \qquad \ldots (1)$$

where, $(P(x)|H_1)$ and $(P(x)|H_0)$ are probability density function of binary hypothesis H_1 (PU present) and H_0 (PU absent) respectively. The log likelihood ratios are translated to the probability of detection (P_D) of PU. The sensing is based on comparing the test statistics, T (based on average power of the received signal, x_n^2) with threshold; if threshold exceeds it is decided that hypothesis H_1 is true otherwise hypothesis H_0. The signal-to-noise (SNR) ratio of the received signal can be expressed as (2) when σ_x^2 and σ_w^2 are signal and noise power respectively.

$$\text{SNR} = \sigma_x^2/\sigma_w^2 \quad \text{... (2)}$$

The threshold (λ) is calculated using the principle of constant false alarm rate as,

$$\lambda = Q^{-1}(P_{FA}\sqrt{2N} + N)\,\sigma_w^2 \quad \text{... (3)}$$

where, Q is standard Gaussian complementary cumulative distribution function (CCDF), N is the number of signal samples and P_{FA} is probability of false alarm. The efficiency of detection method depends on the accuracy of the threshold. Decision statics combined with SNR are translated to probability of detecting PU and these results are used in next step of cooperative game for spectrum allocation.

2.2 Spectrum allocation using game theory

A cooperative game (N,v) is considered with a finite set (N) of players and their characteristic function v, denoting the worth of a coalition S (group of players). Mathematically the characteristic function $v(S)$, is given as[27]:

$$v(S) = |S| \sum_{j=1}^{M} \frac{1 - H(|\max_{\forall i \in S}(P_{ij}, D_j)}{C_S(j)} \quad \text{... (4)}$$

where, S is coalition with any finite set of players {1,2,.., M }, |S| represents the cardinality of the set S, and $C_S(j)$ is the total number of entities sensing channel j, and D_j is the spectrum decision for channel j (+1 when PU present and -1 when PU absent).

A *reward* is jointly assigned to each SU according to his effort done in reducing the uncertainty about PU's activity. Since there is no priori information about PU's activity, it is assumed to be random, thus, the probability of deciding that the PU is active is 0.5. Binary entropy function H(.) measures the amount of uncertainty associated with detection probabilities. Thus the uncertainty associated with PU's activity before sensing the channel is at its maximum with a value of H(0.5) = 1. This reduction in uncertainty quantified as *reward* or *worth* of SUi, denoted as characteristic function $v(i)$ is given as[27]:

$$v(i) = 1 - H(p_{ij}) \quad \text{... (5)}$$

where, P_{ij} is the probability of detecting PU by SUi on channel j.

An allocation (x_1, x_2, ...x_n) is called to be in the *core* of the game if it is found to be individually rational and efficient for each and every subset (coalition) S of N. A coalitional game with transferable pay-off *i.e. transferable utility (TU)* has a non-empty core only if it is balanced. Allocation in the *core* is obtained by means of bargaining among players. When there are many players in a game, it becomes tedious to solve for the system of inequalities and find a solution through bargaining. The *Shapley value* is a one-point-solution that has been introduced in cooperative game to arrive at fair allocation ratio without solving the core. This singleton solution provides payoffs to SUs which can be used as currency in the allocation process to access the unoccupied channel. For any coalitional TU game (N,v), the Shapley value $\varphi(v)$ assigns the payoff $\varphi_i(v)$ is given as[27]:

$$\varphi_i(\mathrm{N}, v) = \frac{1}{|\mathrm{N}|!} \quad \mu_i(\mathrm{S_i(R)}) \ \text{ for each } i \in \mathrm{N} \quad \text{... (6)}$$

where, R is the set of all the $|N|!$ orderings of N, μ_i is the marginal contribution of user i in a coalition S and $S_i(R)$ is the set of players preceding player i in the ordering R.

Now, using the payoff values from (6), SUs purchase the rights to access the unoccupied channel through auctioning[32]. The Vickrey-auction is a second price sealed-bid auction in which bidder who wins the auction, pays the amount of the second highest bid. Vickrey auction design merged with Clarke-Groves design for multiple units, referred as Vickrey-Clarke-Groves (VCG) auction mechanism, claims to facilitate feasible scheduling to allocate the idle channels to SUs based on their channel conditions, payoffs and data rate requirements[27]. The highest bidding SU is allocated a channel that is best for him (in terms of channel capacity) and is charged a price equal to the second highest bid plus a bid increment. This price is now subtracted from the bid of SU who was just allocated the channel and bids from SUs are rearranged to allocate remaining idle channels in a similar manner. VCG auction maximizes total utilities of all SUs and is hence considered to be socially optimal.

3 Experimental validations on WARP

All simulated operations between transmitter and receiver *i.e.* modulation, energy detection, power spectral density detection and allocation are done using MATLAB-2018b and Xilinx iMPACT. The Shapley values are computed using TUGlab toolbox (Transferable Utility Games laboratory)[33].

The hardware setup is as shown in Fig. 2**.** Wireless Open-Access Research Platform (WARP) boards (Mango Communications, USA) fitted with RF module (2.4/5 GHz), ADC/DAC card and v3 Virtex-6 board on a common platform are used. The transmitter antenna is connected to transmitter board and the receiver antenna is connected to receiver board. The transmitting WARP node, receiving WARP node and host PC with WARP Lab7 and simulation software are connected to a common Ethernet switch (1Gbps) to establish the communication link. Transmission and Reception of the signal are performed wirelessly. Software defined radio (SDR) based WARP board, has a reconfigurable field programmable gate array (FPGA) for performing signal processing applications[34]. It supports different radio boards at the front end. The WARP FPGA board and radio board performs baseband processing and converts the intermediate frequency (IF) to analog radio frequency (RF) signal with specified centre frequency. The RF antenna radiates the RF signal.

A cognitive radio environment is modelled with a set of five users wherein two users (PU_1, PU_2) are assigned as primary users and three users (SU_1, SU_2 and SU_3) are assigned as secondary users (*i.e.* cognitive user) which are spatially distributed over available spectral band of 5MHz. The SUs intend to follow the decentralized cooperative approach and access the unused licensed spectral band using cooperative game model. Probability of detecting the PU signal is computed using test statistics of energy detector for 1000 iterations. Simulation parameters are included in Table 1. The transmitted signal obtained from transmitter node is modulated into a Binary Phase Shift Keying (BPSK) signal which is passed through Additive White Gaussian Noise (AWGN) test channel. The received signal is passed through the energy detection block. The power spectral density (PSD) output of received signal is used to monitor the spectral environment about the occupied and vacant spectrum slots using NP hypothesis. Allocation by OSA approach is compared with cooperative game approach using Shapley values

Table 1 — Simulation parameters.

Carrier Frequency	1, 2, 3, 4, 5 MHz
Sampling frequency	12 MHz
SNR, dB	−30, −20, −10, 0, 10
Threshold, λ	1.0266 at P_{FA} = 0.05 and SNR = 10 db

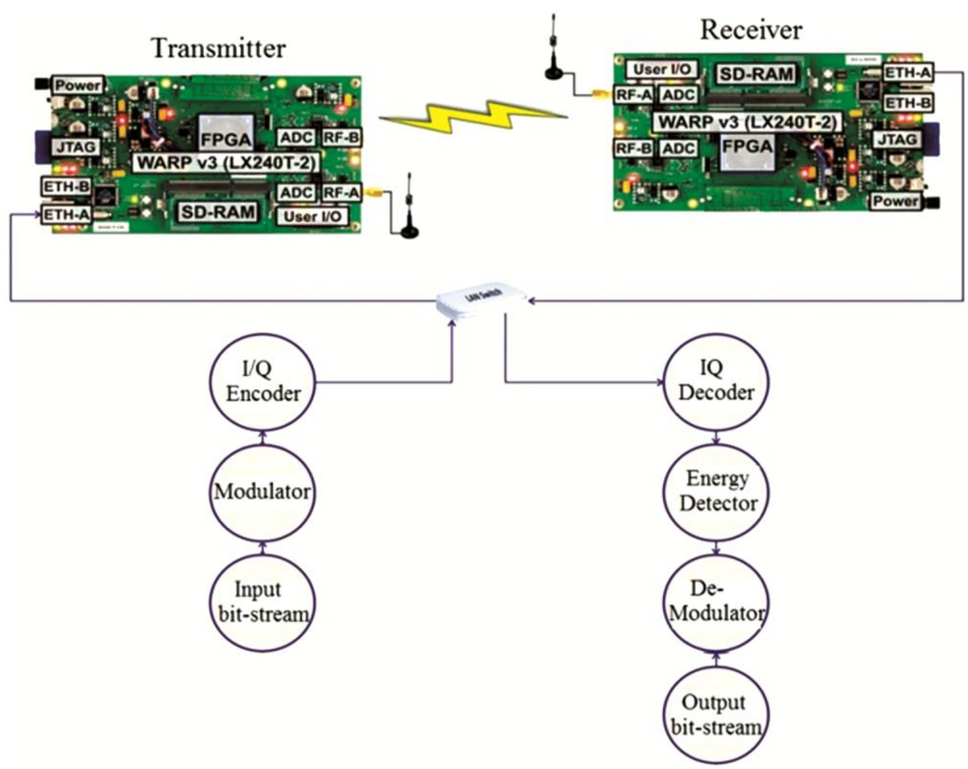

Fig. 2 — Experimental Setup

for VCG auctioning. Steps followed to achieve the proposed objective are illustrated as flow chart (Fig. 3). Performance analysis of system is carried in terms of P_D, P_{FA} and the time–consumed in sensing-cum-allocation jointly, so as to evaluate the system's efficiency towards accuracy and time available for SU's to access the vacant slot.

4 Results and Discussion

The effect of noise on the performance of energy detector is recorded. Figure 4 shows periodogram obtained for BPSK modulated signal in AWGN channel at different SNR values (-30,-20 and 0 dB). It is evident from periodogram that, at very low SNR channels are unable to sense the received signal due to very high noise. Resolution of received signal as busy or idle slots (*i.e.* spectrum hole) starts improving on increasing the SNR to 0 dB and above. Thus probability of detection (P_D) for spectrum hole increased with increasing SNR and reached unity at SNR −5 dB and above. These results are in concordance with earlier reported sensing studies based on energy detection[31].

For allocation of idle spectrum to SUs, the cognitive radio system continuously monitors for spectrum hole through PSD estimates as periodogram and Welch periodogram obtained in energy detection method. Energy of occupied channel/slot is compared with that of free channel. The higher frequency peaks in periodogram and corresponding sharper peaks in the respective Welch periodogram then that of the *threshold value* are marked as the occupied or allocated channel and the lower frequency peaks are indicative of idle/ free channel designated as spectrum holes (Fig. 5). It is evident that Welch method revealed well resolved periodogram with high contrast and higher difference in the spectral power density of the occupied and free band as compared to periodogram method.

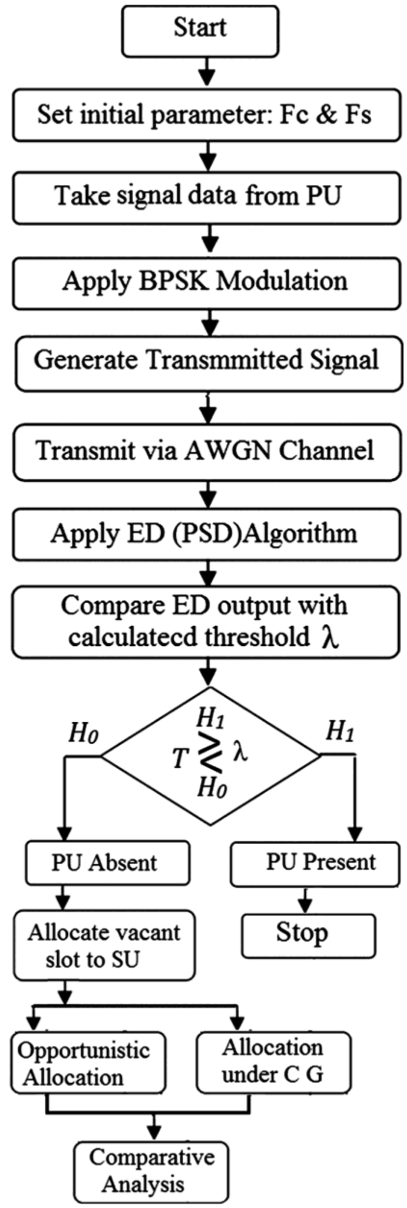

Fig. 3 — Spectrum Sharing Model

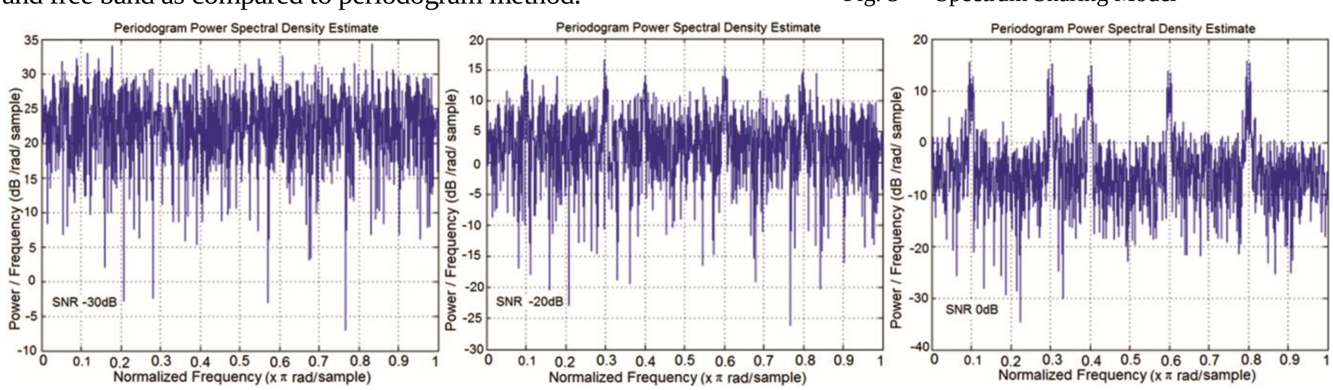

Fig. 4 — Periodogram showing PSD estimate of BPSK modulated signal transmitting in AWGN channel at SNR −30 dB, −20 dB and 0 dB.

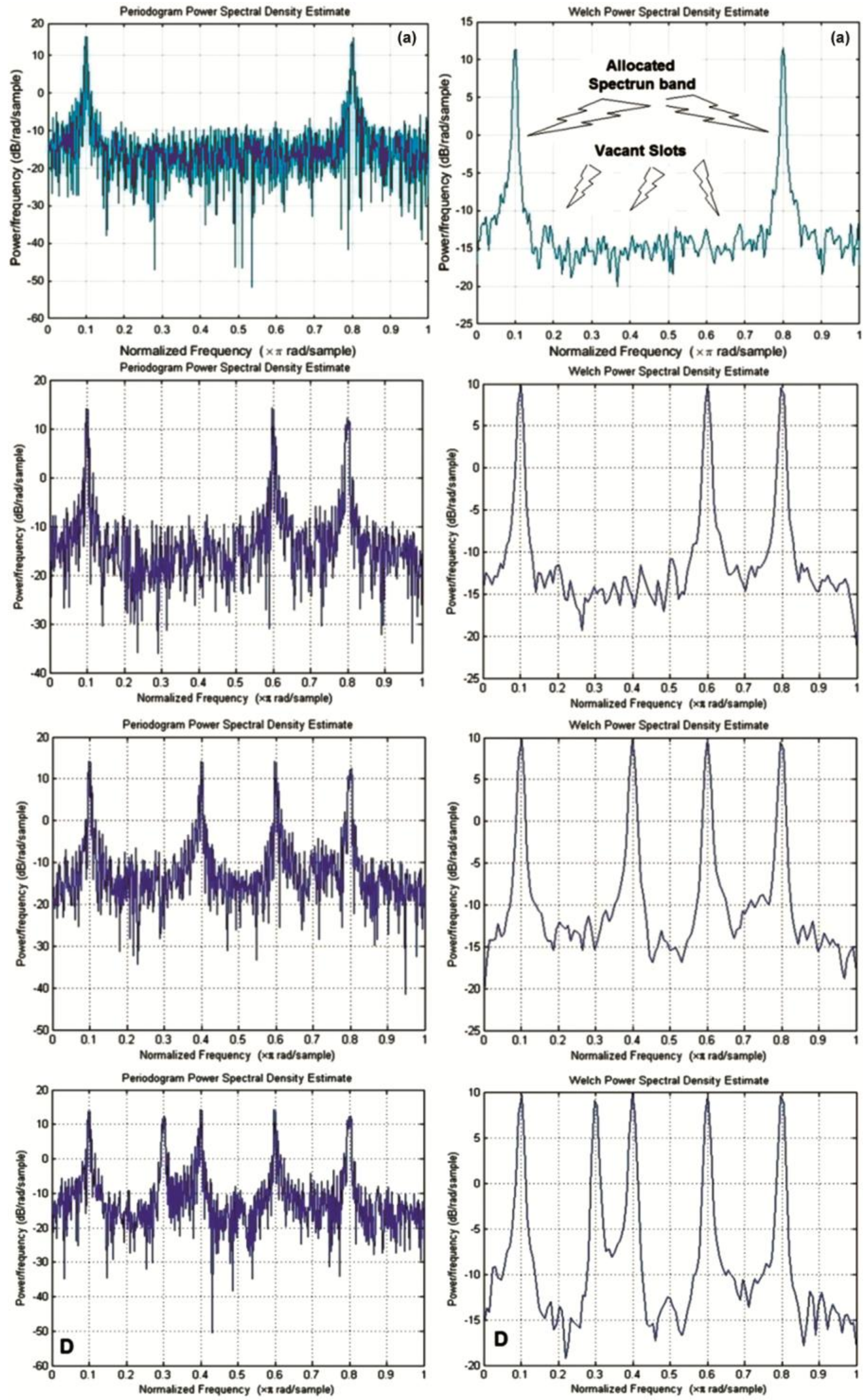

Fig. 5 — Periodogram and Welch curves showing slot allocation position multiple slots. (A): PU1, PU2; (B): PU1, PU2, SU1; (C): PU1, PU2, SU1, SU2; (D): PU1, PU2, SU1, SU2, SU3.

It is assumed that the primary user, PU_1 and PU_2 are present at 1st and 5th slot referred as channel CH_1 and CH_5, rest of the slots/channels are unoccupied, this stage is depicts in curve A, Fig. 5. Now the communication system will look for the first available vacant slot and automatically assign it to the SU. Slots 2nd, 3rd and 4th as channel CH_2, CH_3 and CH_4 are identified as spectrum holes where no activity of PU is recorded, confirming that PU is absent. The first available spectral gap is occupied by the SU1 resulting is an increase in power of CH_2 (curve B, Fig. 5). Now the system will again search for the next spectrum hole and automatically assign CH_3 to SU_2 (curve C, Fig.5) and finally the allotment of 4th slot as CH4 to SU3 is evident in curve D, Fig. 5. Once all the slots are being assigned, the system will not entertain other secondary users. This first-come-first serve basis spectrum allocation is opportunistic spectrum access (OSA) approach of spectrum sharing. Thus spectrum sharing in CRNs is demonstrated successfully without interfering with the frequency bands used by the licensed PUs.

To illustrate the joint approach for spectrum sharing as cooperative game in CR networks, a scenario is consider where three secondary users SU_1, SU_2 and SU_3 wish to cooperate and share the idle channels of licensed band subdivided into five channels CH_1, CH_2, CH_3, CH_4, CH_5 and assuming there is no priori information about primary user's activity. A decentralized cooperative sensing approach is used where a fusion centre (FC) manages the sensing and access policy of SUs through a common control channel. For convenience, we assume the first SU to enter the network as the FC. Detection probability using Neyman–Pearson detection strategy from each SU is combined at FC. SUs sense the channels and translate SNRs to probability of detecting PU under a fixed probability of false alarm $P_{FA} = 0.05$; the results of present simulations as shown in Fig. 6a. The receiver operating characteristic (ROC) plots showing P_D vs P_{FA} for energy detector at 10dB SNR is shown in Fig. 6b.

Table 2 includes spectrum sensing map, SNR values, probability detection P_D matrix for SUs and PUS and decision about the occupancy state of channels. *Spectrum sensing map* is created by FC shows the channel occupancy by SUs. A SNR matrix has been created for the channels that are sensed by SUs; the SNR values are collected from random uniformly distributed variable between −30dB to 10 dB. Now, the SNR matrix is translated into probability of detection for SUs using equation (2) at constant P_{FA}. For PUs the P_D is taken as 0.5, since in the absence of any prior knowledge about PU's activity, it is assumed to be random (refer section 2.2). The P_D matrix of SUs and PUs is sent to FC, where they are combined to give decision about the idle channel. A standard simplistic assumption of *equal gains combining* fusion rule is adopted by FC. The decision about presence of PU is denoted by +1, whereas absence of PU is denoted by −1 as shown in Table 2. The transmission requirements of the SUs are quantified in terms of data rates or channel capacity. The channel capacity of a 5MHz bandwidth for AWGN channel with SNR values drawn from a uniform distribution between -30 dB and 10 dB is estimated using Shannon's capacity formula and the values are included in Table 3. SUs

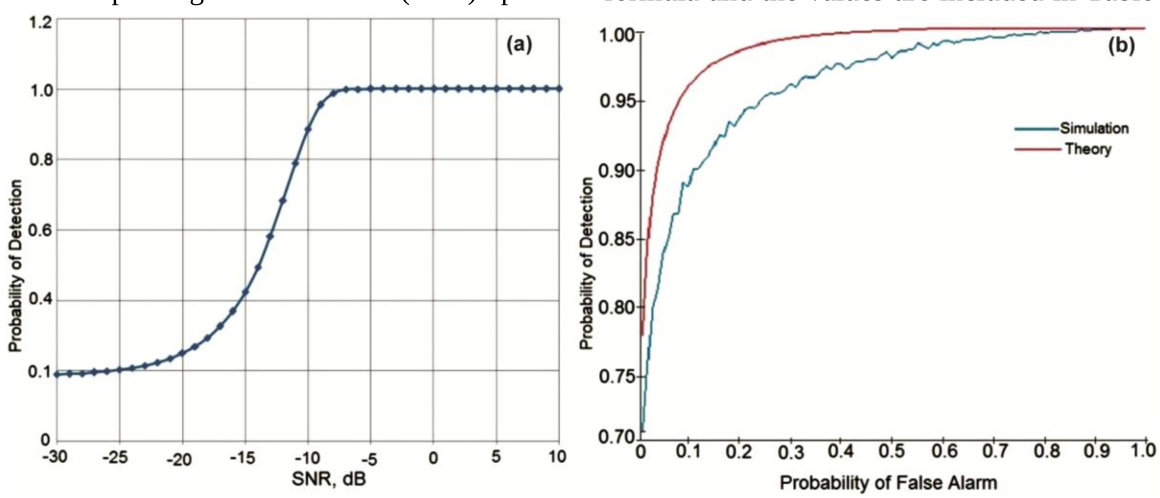

Fig. 6 — a. P_D of PU *vs* SNR at constant P_{FA} (=0.05) and b. ROC Curve P_D *vs* P_{FA} at SNR 10dB

Table 2 — Simulation results: Sensing Map, SNR matrix by SUs, P_D values and decision on idle channel.

	Sensing Map					SNR Matrix					P_D Matrix				
Channel→	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
SU_1	○	●	●	●	○	-	-20	-12	-15	-	0.5	0.3565	0.7788	0.5430	0.5
SU_2	○	●	●	○	○	-	-17	-09	-	-	0.5	0.4390	0.9757	0.5000	0.5
SU_3	○	●	○	○	○	-	-22	-	-	-	0.5	0.3160	0.5000	0.5000	0.5
Decision →											−1	+1	+1	+1	−1

'○' represents occupied channel and '●' represents idle channel

choose the channels they prefer to sense according to their data rate requirements.

The characteristic function of cooperative game based on reduction on uncertainty about PU's activity is then calculated using equation (4). The *reward* that a SU acquires from sensing the channel is quantified from *reduction in uncertainty* about PU's activity, computed using equation (5). The *rewards* of SU for present simulation in presence and absence of PU are shown in Fig. 7

Each SU receives a reward for its effort done in the sensing process. The rewards acquired are the worth of SUs that are being used to calculate the payoffs using one-point solutions based on Shapley values. The payoff values of respective SUs as per equation (6) are: 39.1600 (SU1), 28.6667 (SU2) and 32.1667 (SU3). These payoff values, included in Table 3(b) are used as currency during bidding for channel access and reflect SU's expectations based on their transmission needs. Results are in concordance with the simulations carried out in reference[27].

Table 3 — Channel capacity and channel allocation based on VCG auction.

User →	SU_1	SU_2	SU_3
a. Channel Capacity (Mbps)			
CH_2	0.9930	0.0687	0.8485
CH_3	0.0243	0.0535	0.9998
CH_4	1.6465	0.7218	0.0618
b. Channel Allocation			
Payoffs*	39.1600	28.6667	32.1667
c. First round of bidding			
SU's Bids	12.7611	25.6612	18.9211
Price paid	--	18.9212	--
Channel allocated	--	# CH_4	--
Data rate achieved, Mbps	--	0.7218	--
d. Second round of bidding			
Bids	12.7611	6.7400	18.9211
Price paid	--	--	12.7612
Channel allocated	--	--	# CH_3
Data Rate achieved, Mbps	--	--	0.9998
e. Second round of bidding			
Bids	12.7611	6.7400	6.1599
Price paid	7.7400	--	--
Channel allocated	# CH_2	--	--
Data Rate achieved, Mbps	0.9930		
Balance Payoffs	31.4200	9.7455	19.4055

**as per Shapley value*

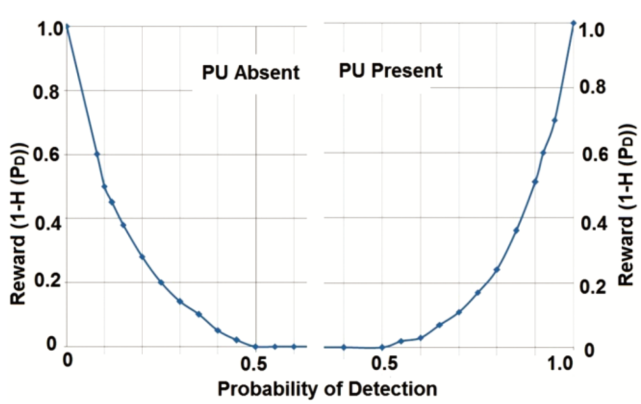

Fig. 7 — Reward for SU based on reduction of uncertainty about PU's activity

Channel allocation based on VCG auction mechanism has been carried out. According to the payoff values, SU_2 has the highest bid and the best unoccupied channel for SU_2 in terms of obtainable data rate is channel CH_4. Thus in first round of bidding, SU_2 gets access to channel CH_4 at the price of second highest bidder (*i.e.* of SU_3) plus one bid increment *i.e.* a price of 18.9212. Now for second round of bidding, the bid of SU_1 and SU_3 are restored whereas for SU_2, the price paid in first round is deducted from the bid and the new bid for is obtained and auction is continued. Now SU_3 is the highest bidder and best channel for her is channel CH_3. SU_3 pays a price of 12.7612 to get access to channel CH_3. The same process is repeated for third round of bidding and SU_1 get access to channel CH_2 for a price of 6.7401. The final allocation is shown in Table 3.

VCG auction does not guarantee data rate maximization; however the resources allocated in first round are deducted from the bid and the new bid of SU_2 is obtained. Bids are sorted again and auction is continued. The SU_3 is now the highest bidder and the best unoccupied channel is CH_3. SU_1 is the second according to SU bids and hence satisfy the data rate requirements of the SUs in a fair manner. The allocation time for opportunistic spectrum access (OSA) approach is as computed to be 122 ms and that of dynamic spectrum access (DSA) using cooperative game theoretic model with Shapley values for VCG auction is 107ms. The later approach has shown to consume less time; as a result more number of users can share the channel. Thus the allocation under cooperative game is considered to be spectrum efficient as all the channels are occupied at any given time, leaving no idle channels with minimum allocation time.

5 Conclusions

A MATLAB based simulation has been carried out for cognitive radio based joint framework for spectrum sharing wherein spectrum sensing follows a decentralised cooperative approach and spectrum access strategies are based on a cooperative game for their real time implementation on WARP. Energy detection by periodogram and Welch method to provided the PSD estimates for spectrum sensing and monitoring spectrum holes. The cooperative game (CG) model has shown to provide SUs with an incentive to cooperate. Based on their worth, SUs get payoffs which were computed using Shapely values as one-point solutions and allocation through a Vickrey–Clarke–Groves auction mechanism. This mechanism allocates the best possible channels to SUs according to their bids and hence satisfies their data rate requirements in a fair manner. The algorithm exhibit superior performance in terms of reduced sensing time and allocation time resulting in a spectrum efficient communication system as channel can be shared by more number of users. It is envisaged to extend the proposed spectrum sharing model for complex spectrum sharing systems, taking into account of more parameters like interference management and energy efficiency in a heterogeneous cognitive environment.

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