Performance Optimization of the MIMO-OFDM Based Adaptive Cognitive Radio System using a Hybrid Channel Access Scheme

Santosh Itraj, Uttam Bombale, Pravinkumar Patil, Meenakshi Patil

Abstract: ***The cognitive radio is a promising candidate to resolve the issues created due to the spectrum scarcity in wireless communication. The main motive of CR technology is to create communication opportunities by sensing and learning from the external environment thereby improving the spectrum usage efficiency. The integration of the link adaptation, MIMO-OFDM with CR technology gives the utmost performance. In this treatise, we propose the hybrid channel access (interweave-underlay) scheme for the MIMO-OFDM based adaptive CR system. We have investigated the performance of the CR system under a hybrid channel access (interweave-underlay) scheme as well as underlay channel access scheme. We consider the binary stochastic model to reflect the primary user (PU) activities. The performance is evaluated with different channel detection probabilities under perfect as well as imperfect (false alarm) spectrum sensing environment. The result shows the significant improvement in the throughput of the system in proportion with the higher-quality channel detection probability with perfect spectrum sensing. This exploits the hybrid channel access scheme as one of the techniques to optimize the performance of the system. This signifies the importance of the optimum channel sensing and its selection in improving the performance of the system. To show the performance improvement of the CR system using hybrid channel access scheme we have compared it with the performance of the CR system based on the conventional underlay channel access scheme. The proposed scheme can be used to improve the performance of the entire CR network.***

Keywords: ***Cognitive radio, hybrid scheme, OFDM, throughput, BER.***

I. INTRODUCTION

The exponential growth in wireless technology and its end users along with their demands resulted in overcrowding in the unlicensed Industrial Scientific and Medical (ISM) band. This results in congestion, which eventually affects the QoS of the entire communication system.

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However, as per the report given by the Spectrum Policy Task Force of the Federal Communication (FCC), the licensed bands have 15 to 20 % utilization based on a time slot, geographical location. This reflects the underutilization of the licensed spectrum [1].

This inefficient and unbalanced utilization of the spectrum results in spectrum scarcity. The cognitive radio (CR) is a key to resolve the issues that arose because of the scarcity of precious resources like spectrum, energy, etc. CR is a smart device, which senses environment, learns from it, and adapts the operating parameters to the hostile RF environment to optimize the performance of the system [2].

CR allows secondary users (SUs) (unlicensed users) to use the licensed spectrum owned by the primary users (PUs) in an opportunistic way without affecting QoS of the PUs. CR technology allows SUs to access the licensed spectrum based on the different spectrum access schemes such as underlay, overlay, and interweave [3], [4], and [5]. In the underlay channel access scheme, SU is allowed to coexist with the PU under the constraint of transmission power below the noise floor threshold of the PU. This imposes the limitation on the performance of the SU. In the case of the interweave channel access scheme, SU is allowed to access the spectrum of the PU in the opportunistic way i.e. SU can use the spectrum of the PU only in his absence. The interweave channel access scheme can be exploited to enhance the throughput of the system by selecting the higher-quality channel that too which allows SU to use the channel for more time span [6]. The combination of the underlay and interweave channel access scheme results in a hybrid channel access scheme. The hybrid channel access scheme can be combined with the link adaptation, MIMO-OFDM technology to get the utmost performance of the CR system. Many researchers have worked on the achievable transmission data rates of the SU by considering underlay or overlay channel access schemes [7], [8], and [9]. In [6], authors have investigated the achievable transmission rate of the SU with a hybrid channel access strategy. The performance has been investigated under the constraints of the SU transmission power, interference to the PU, and BER requirement of the secondary link. The throughput improvement with the proposed scheme has been observed. The interweave channel access scheme for cognitive users has been proposed in [10]. The proposed scheme is based on the traffic characteristics of the primary system and the Doppler spread of the cognitive user. It has been realized that, in case of highly correlated primary traffic or dynamic behavior of the cognitive user, Frequent channel switching is not beneficial in improving the throughput of the system. The proposed scheme is based on the traffic characteristics of the primary system and the Doppler spread of the cognitive user.

It has been realized that, in case of highly correlated primary traffic or dynamic behavior of the cognitive user, frequent channel switching is not beneficial in improving the throughput of the system. The performance improvement in the CR network based on a hybrid (interweave-underlay) channel access scheme has been proposed in [11]. The scheme is investigated under a perfect spectrum-sensing environment with the objective of optimizing the throughput performance of the system. In this case, the hybrid scheme is modeled as a continuous-time Markov chain. The significant improvement in the throughput of the SU has been observed. The scheme based on the hybrid overlay-underlay spectrum access to improve the throughput and outage probability has been proposed in [12]. In [13], the authors proposed the new frame structure for the SU to predict the status of the channel and select the channel that has been predicted as idle based on history. The proposed prediction technique shows significant improvement in the throughput of the SU. Many of the researchers have worked on the channel sensing based on the different channel prediction techniques such as artificial neural network to improve the performance of the SU [14], [15].

In the majority of the research work on cognitive radio, the focus has been given on optimizing the throughput, energy efficiency by using link adaptation. The cognitive systems considered in these cases are based on the underlay channel access scheme. In the aforementioned literature, some of the researchers have focused on the optimization of the performance of SUs using hybrid (interweave-underlay, underlay-overlay) channel access schemes. As evident from the above discussion, it can be realized that the hybrid channel access scheme can be exploited as one of the techniques to enhance the throughput of the SU system. However, in most cases, the performance is investigated by considering perfect spectrum sensing condition and no consideration has been given to the imperfect channel-sensing environment (false alarm). The effect of variable channel detection probabilities has not been observed and it is necessary for designing accurate channel sensing and channel detection algorithms.

In this treatise, we propose the hybrid (interweave-underlay) channel access scheme for MIMO-OFDM based adaptive CR system. The considered SU system is a performance-optimized system by adapting rate, MIMO profile, and transmission power. To upgrade the performance of the adaptive SU system the problem of optimization of the throughput of the SU using the hybrid channel access scheme has been formed. The throughput optimization is under the constraint of the targeted BER and the maximum average transmission power. The performance of the system is investigated with different channel detection probability values in perfect as well as imperfect spectrum sensing environment. The performance of the system with a hybrid strategy is compared with the performance of the system based on the underlay channel access scheme.

The rest of the paper is organized as follows: Section II describes the system model for a hybrid (interweave-underlay) channel access scheme. Section III describes the channel selection algorithm to implement a hybrid channel access scheme. Section IV presents the simulation results and finally, the conclusion is given in section V.

II. SYSTEM MODEL

A. System description

The system model for the proposed cognitive radio system is shown in Figure 1. It comprises two primary users PU_i, PU_u, and two secondary users *SU1*, *SU2*. It. is presumed that the primary users are the license users of the TV spectrum. The spectrum of the PU_i is represented as CH_i and that of the PU_u is represented as CH_u. These channels are Rayleigh distributed and modeled as TGn (Throughput Task Group) channels. It is assumed that *SU1* transmits the data to *SU2* by using channel either CH_i or CH_u. Here we consider that the secondary user access CH_i in an opportunistic manner i.e. *SU1* communicates with *SU2* only when PU_i is absent, and on the arrival of the PU_i it vacates the channel CH_i. Thus *SU1* uses CH_i in an interweave manner. However, it is assumed that the primary user PU_u allows the *SU1* to use CH_u for communication with *SU2* in an underlay manner. In the case of the underlay channel, access scheme the transmission power of the *SU1* is restricted to the interference threshold of the PU_u. The interference threshold in the proposed system is assumed to be 1 W. The maximum transmission power of the *SU1* in the absence of the primary user is 2W. We consider that the CH_i is of the higher-quality compare to that of the CH_u. Hence, *SU1* gives higher priority to the CH_i and prefers the communication over the channel CH_i when it is idle otherwise, *SU1* communicates with *SU2* continuously over the channel CH_u. It is presumed that PU_u is continuously in an active state and allows *SU1* to access CH_u with constrained transmission power and hence limiting the performance of the secondary system. The activity of the PU_i is modeled as an independent binary stochastic process. It is approximated as a random ON-OFF model. Thus, in the proposed adaptive cognitive system *SU1* communicates with *SU2* using hybrid i.e. interweave-underlay channel access scheme to exploit the benefits of both schemes.

B. Mathematical model

In the proposed system, SUs are equipped with $N_t = 2$ transmit antennas and $N_r = 2$ receive antennas. It is assumed that the transmission power is equally distributed among the multiple transmit antennas. The system supports (2 × 2) spatial division-multiplexing mode (SDM) and (1 × 2) space-time block code (STBC) mode. The system adapts MCS, MIMO profile (STBC/SDM) and transmission power. The secondary system is based on the specifications of the 802.11n standard considered as an example standard. The adapted parameters are defined for each of the packets to be transmitted. The power adaptation is based on the packet-based water-filling technique, used for the optimization of energy efficiency [16]. The secondary user *SU1* communicates with *SU2*

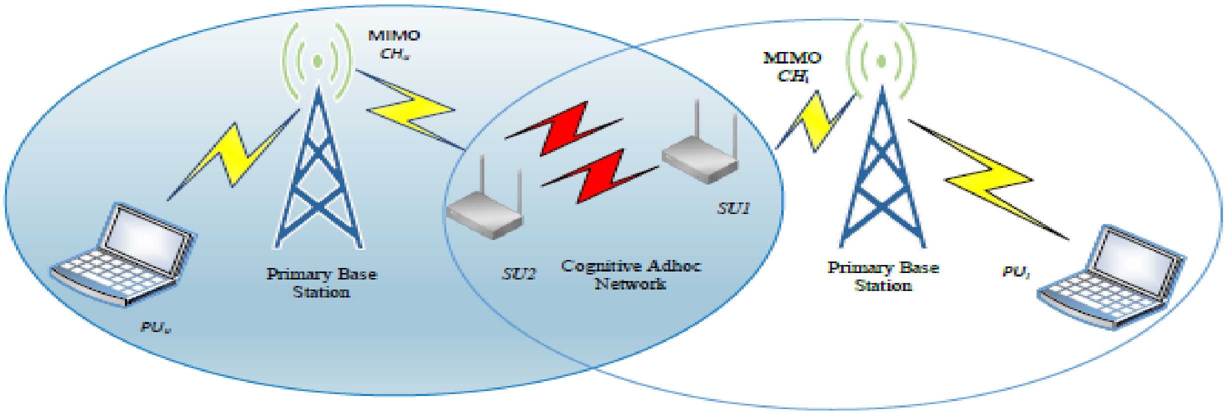

Fig.1. System model

by using a hybrid (interweave-underlay) channel access scheme. The received signal at the secondary user *SU2* on the channel CH_i, that is accessed in an interweave manner is

$$y_i = H_i x_i + w_i \tag{1}$$

Where H_i is the channel gain matrix of size (2 × 2). The element H_{i-21} of the matrix H_i reflects the channel gain between the receive antenna 2 and the transmit antenna 1.

x_i is the transmit OFDM symbol of the size (2 × 1).

y_i is the received OFDM symbol of the size (2 × 1).

w_i is a (2×1) noise vector, the element w_{i-j} is a white Gaussian noise with zero mean and a variance σ_{in}^2.

Similarly when *SU1* access CH_u in an underlay manner, the received signal at the *SU2* is

$$y_u = H_u x_u + w_u + w_{ps} \tag{2}$$

Where y_u , H_u and w_u have the same meaning as that of y_i, H_i and w_i for CH_i, w_{ps} is the noise vector defining the noise present at the *SU2* receiver antennas due to the presence of the PU_u.

Where w_{ps} is defined as

$$w_{ps-1} = p_{p2} h_{ps2} \tag{3}$$

Where p_{p2} is the transmission power of the PU_u, h_{ps2} is the channel gain between the primary *user* PU_u and the secondary user *SU2*. The element w_{ps-1} of the vector w_{ps} is the noise present at the receive antenna 1 due to the presence of the PU_u. The receiver at the *SU2* computes the channel estimate using a minimum mean square technique (MMSE). The computed channel estimate is used to compute the SNR estimate (CSI) at the receiver.

The proposed system is designed with an objective of optimizing the throughput of the SU under the constraint of the targeted BER of 10^{-1} and maximum average power of 2 W and in case of the underlay channel access scheme it is 1W. The maximum achievable throughput of the *SU1* while communicating over CH_i with *SU2* in an interweave channel access scheme is given as [17]

$$Thr_{i-\max} = B\log_2\left(1+\frac{P_{si}h_i}{w}\right) \tag{4}$$

Where B is the channel bandwidth, P_{si} is the transmission power of the *SU1*, h_i is the gain of the channel CH_i, w is the additive white Gaussian noise (AWGN) power.

In the case of the underlay channel access scheme, *SU1* transmits with reduced power to avoid interference to the PU_u. Thus, the maximum achievable throughput of the *SU1* gets reduced and is given as

$$Thr_{u-\max} = B\log_2\left(1+\frac{P_{su}h_u}{w+P_{pu}h_{ps2}}\right) \tag{5}$$

Where P_{pu} is the transmission power of the PU_u, P_{su} is the transmission power of the *SU1* operating in underlay channel access scheme, and h_{ps2} is the gain of the channel from PU_u to the *SU2*.

The BER for the BPSK, QPSK, and M-QAM constellations for the proposed scheme are as defined in [16].

For e.g. the BER in case of the BPSK is

$$P_b = \frac{1}{\log_2 M}\left[\frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left(M_{\gamma_b}\left(\frac{-g}{\sin^2\phi}\right)\right)^L d\phi\right] \tag{6}$$

Where $M_{\gamma_b}(s)$ is the moment generating function (MGF) of the average SNR per bit $\bar{\gamma}_b$ for all L_D channels and for Rayleigh fading channel it is given as

$$M_{\gamma_b}(s) = (1-s\bar{\gamma}_b)^{-1} \tag{7}$$

Here

$$s = -\frac{g}{\sin^2\phi} \tag{8}$$

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Where g is one for the coherent BPSK constellation.

The throughput of the system in terms of the packet error rate (*PER*) is

$$Thr = \left(1 - PER\right) \tag{9}$$

Where PER is expressed as

$$PER = \left(1 - \left(1 - BER\right)^{p_l}\right) \tag{10}$$

Where p_l is the packet length.

The average throughput of the system considering interweave and underlay access schemes with perfect spectrum sensing is given as

$$Thr_h = \left(P_{di}\right)\left(Thr_i\right) + \left(P_{du}\right)\left(Thr_u\right) \tag{11}$$

In the case of the imperfect spectrum sensing the throughput of the system becomes

$$Thr_h = \left(P_{di}\right)\left(Thr_i\right) + \left(P_{du} + P_f\right)\left(Thr_u\right) \tag{12}$$

Where Thr_i is the average throughput of the secondary system when it communicates over CH_i and Thr_u is the average throughput of the secondary system when it communicates over CH_u, P_{di} and P_{du} are the true channel detection probabilities associated with channel CH_i and CH_u respectively, P_f is the false alarm probability.

III. ALGORITHMS

In this section, we discuss the proposed algorithm for optimizing the throughput of the MIMO-OFDM based adaptive cognitive system by using a hybrid (interweave-underlay) channel access scheme. The algorithms are proposed for sensing the status of the channels (CHAN-SENSE) and selecting the appropriate channel for communication between secondary users (CHAN-SELECT). The proposed scheme is implemented for sensing the availability of the higher-quality channel (CH_i). Then based on the outcome of the channel-sensing algorithm and the predefined channel detection probability values (true detection, false alarm) the appropriate channel is selected by using the channel selection algorithm. This problem can be formulated as

$$\underset{M_I,\, P_{mavg-t},\, CH}{Max} \quad Thr\left(CH\right)$$

Subject to:

$$\begin{cases} C(1): & M_I \in \left\{M_0, M_1, \ldots, M_i\right\} \\ C(2): & CH \in \left\{CH_i, CH_u\right\} \\ C(3): & P_{mavg-t} \le P_{mavg-\max} \\ C(4): & BER \le BER_{target} \end{cases} \tag{13}$$

Where Thr is the throughput of the system, M_I is the set of supported MCS, P_{mavg-t} is the average transmit power per packet over the m^{th} channel, $P_{mavg-\max}$ is the maximum average transmit power over the m^{th} channel and for interweave case it is 2W and in case of underlay channel access scheme, it is 1W. BER_{target} is the targeted BER with value 10^{-1}. The value of i can be over the range of 1 to 16. The average transmission power inserted over m^{th} channel is defined by the packet-based water-filling power adaptation algorithm [16] and is given by

$$P_{mavg-t} = \begin{cases} \dfrac{1}{\lambda} - \dfrac{\sigma_{mn}^2}{\sigma_m^2}, & If \ \dfrac{1}{\sigma_m^2} \le \dfrac{1}{\lambda \sigma_{mn}^2} \\ 0, & Otherwise \end{cases} \tag{14}$$

Where σ_m^2 is the average channel power for the received packet over m^{th} channel, m can be either i or u. λ is Langrage multiplier defined by the power constraint, σ_{mn}^2 is a noise variance at the receiving end.

We consider the binary stochastic process to reflect the activity of the PU. The idle and the busy state of the channel CH is reflected by the hypothesis H_0, and H_1 respectively. The received signal $y_p(n)$ at the SU from the PU can be modeled as [11]

$$y_p(n) = \begin{cases} w(n): & H_0, \\ p(n) + w(n): & H_1 \end{cases} \tag{15}$$

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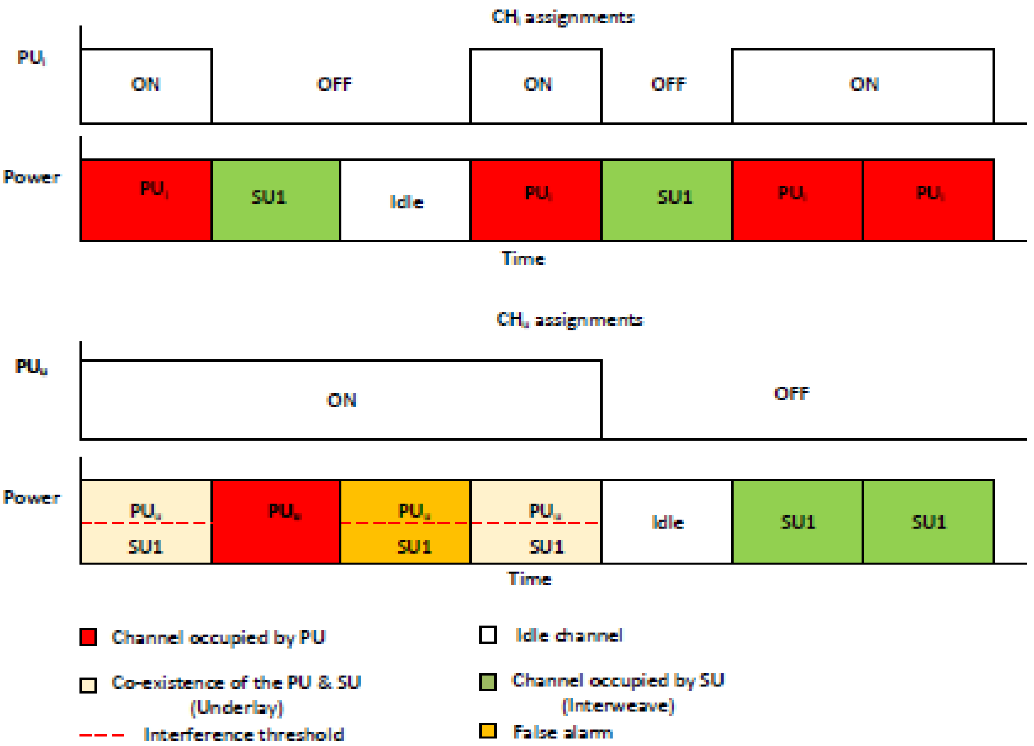

Fig.2. Activities of PUs and channel assignments

Where $w(n)$ is the AWGN signal, $p(n)$ is the signal received at the receiver of SU from the PU.

We consider the perfect spectrum sensing as well as imperfect spectrum sensing conditions in the analysis of the system. The various probabilities (%) considered in the channel sensing and the channel selection algorithms are

(1) The probability of the availability of the $CH_i = P_{av}$.

(2) The probability of the true detection of the $CH_i = P_{di}$.

It signifies the probability of the selection of the channel when it is available.

(3) The probability of the CH_u selection when CH_u is true is given by

$$P_{du} = 100 - P_{di}$$

(4) The probability of the false alarm is defined as

$$P_f = P_{av} - p_{di}$$

The probability of the true detection of the channel is represented as

$$P_d = P\left(H_0 \mid \mathrm{H}_0\right) \tag{16}$$

The probability of the false alarm is defined as

$$P_f = P\left(H_0 \mid H_1\right) \tag{17}$$

The activities of the PUs and the channel assignments based on these activities that are considered in the proposed algorithms are shown in Fig. 2.

A. Channel management algorithm (CHAN-MANAGE)

Channel management algorithm is located at the *SU1* transceiver end; it senses the status of the primary users, defines the availability of the channel by using CHAN-SENSE algorithm, and selects the available channel by invoking CHAN-SELECT algorithm for the transmission of the next packet.

B. Channel sense algorithm (CHAN-SENSE)

This algorithm defines the status of PU_i in a random manner with standard uniform distribution. It requires information about the status of PU_u and probability of CH_i availability P_{av} in percent. The algorithm defines channel availability status as A_i for CH_i and A_u for CH_u respectively.

C. Channel selection algorithm (CHAN-SELECT)

This algorithm is proposed to select the channel to be assigned to the *SU1* for communication with *SU2*. The channel selection is decided by the activities of the PUs that are sensed by the CHAN-SENSE algorithm to define the availability of the channel. It also considers the various channel detection probabilities while selecting the channel.

IV. SIMULATION RESULTS

In this section, we discuss the simulation results of the proposed hybrid (interweave-underlay) channel access scheme for the MIMO-OFDM based adaptive cognitive radio system. The simulation parameters considered in the proposed scheme are depicted in Table- I [18]. The performance of the cognitive radio system is analyzed under the following conditions

A. Perfect spectrum sensing environment.

B. Imperfect spectrum sensing environment.

Table- I: System parameters

No.	System Parameter	Specification
1	WLAN Standard	802.11n HT mode
2	PSDU length	1000 bytes
3	Guard interval	800 ns
4	Channels used	TGn-B, TGn-D, AWGN
5	Maximum packet period	1.3 ms
6	MIMO profiles	STBC (1 × 2), SDM (2 × 2)
7	Operating SNR range	0 dB to 60 dB
8	Channel access schemes	Underlay, hybrid (interweave-underlay)
9	Targeted BER	10-Jan
10	Maximum average transmit power	For CH_i it is 2W, for CH_u underlay it is 1W

.

Algorithm 1 CHAN-MANAGE

Initialisation :
$CH_i \leftarrow 0$
$CH_u \leftarrow 1$
$CP \leftarrow 0$
Function call :
CHAN-SENSE(A_i,A_u)
CHAN-AELECT(CH_i, CH_u, CP)
return CH_i, CH_u, CP

Algorithm 2 CHAN-SENSE

function CHAN-SENSE(P_{av})
Read the channel availability probability (P_{av}) for the channel CH_i.
Initialize the status of the channel.
    $A_i \leftarrow 0$ ▷ CH_i unavailable
    $A_u \leftarrow 1$ ▷ CH_u available
Use the channel availability probability and the output of the random number generator to define the status of the primary user PU_i.
    if ($PU_i = 0$) then
        $A_i \leftarrow 1$ ▷ CH_i available
    else
        $A_i \leftarrow 0$ ▷ CH_i unavailable
    end if
    return A_i, A_u
end function

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Algorithm 3 CHAN-SELECT

```
function CHAN-SELECT(P_av, P_di, P_du, PU_u, A_i, A_u)
  Read the predefined values of the channel detection probabilities P_di, P_du.
  Read the status of the channel availability A_i, A_u.
  Compute the false alarm probability as
     P_f ← (P_av − P_di)
  Initialize the constraint power flag.
     CP ← 0
  Initialize the channel selection as
     CH_i ← 0
     CH_u ← 1                                        ▷ CH_u is selected
  Use channel avilability status and the channel detection probabilities to select the
  channel.
     if (A_i = 0)&(A_u = 0) then                      ▷ PU_i and PU_u present
        CH_u ← 1                ▷ Select the channel CH_u with probability P_du
        CH_i ← 0
        CP ← 1 ▷ Set the constraint power flag to limit the transmission power of
  the SU1
     else if (A_i = 0)&(A_u = 1) then             ▷ PU_i present and PU_u absent
        CH_u ← 1                ▷ Select the channel CH_u with probability P_du
        CH_i ← 0
        CP ← 0                                  ▷ Reset the constraint power flag
     else if (A_i = 1)&(A_u = 0) then             ▷ PU_i absent and PU_u present
        if (P_f = 0) then
           CH_i ← 1             ▷ Select the channel CH_i with probability P_di
           CH_u ← 0
        else
           CH_u ← 1             ▷ Select the channel CH_u with probability P_f
           CH_i ← 0
           CP ← 1▷ Set the constraint power flag to limit the transmission power
  of the SU1
        end if
     else if (A_i = 1)&(A_u = 1) then              ▷ PU_i absent and PU_u absent
        if (P_f = 0) then
           CH_i ← 1             ▷ Select the channel CH_i with probability P_di
           CH_u ← 0
        else
           CH_u ← 1             ▷ Select the channel CH_u with probability P_f
           CH_i ← 0
           CP ← 0                               ▷ Reset the constraint power flag
        end if
     end if
     return CH_i,CH_u, CP
end function
```

A. Perfect spectrum sensing environment ($P_f = 0\%$)

The throughput performance of the system is evaluated for underlay and hybrid (interweave-underlay) channel access schemes with the false alarm probability $P_f = 0\%$ i.e. channel is detected truly on its availability. The system is analyzed with different channel detection probability values. The throughput and BER performances are shown in Figure 3 and Figure 4 respectively. The numerical values of the average throughput for different channel detection probabilities are illustrated in Table-II The throughput curve (*CH*$_u$-*P*$_d$*0*) signifies the performance of the system by considering the underlay channel access scheme and is showing the minimum throughput with the average value of 38.64 Mbps. This is because of the constraints on the transmission power and the noise contributed by the PU_u. The increase in the probability of channel CH_i detection results in more opportunities for the transmission over CH_i for *SU1*. The simulation result signifies that the increase in the probability P_{di} of the channel CH_i detection results in a proportional boost in the throughput of the system. . For e.g. the throughput of the system with probability $P_{di} = 20\%$ (*CH*$_u$-*P*$_d$*20*) is 40.90 Mbps and with $P_{di} = 80\%$ (*CH*$_u$-*P*$_d$*80)* throughput becomes 50.10 Mbps. In case of the probability, $P_{di} = 100\%$ i.e. CH_i is available for transmission of all the predefined packets the throughput is at its maximum value of 53.58 Mbps. The system considered in the proposed scheme is MIMO-OFDM based adaptive cognitive radio system. The system adapts rate, MIMO profile (STBC/SDM), and average transmission power according to the behavior of the hostile RF environment. The mean average transmission power required in all the considered cases is illustrated in Table-II. It can be realized that the communication in all cases uses less power than the maximum average allowable power (i.e. for interweave case 2 W and for underlay case 1 W). This efficient energy utilization is ensured by the packet-based water-filling power adaptation scheme [16]. The BER curves in all the considered cases reflect that the BER is less than the targeted BER in the proposed scheme ensuring the required QoS.

B. Imperfect spectrum sensing environment ($P_f = 60\%$)

In the case of the imperfect spectrum sensing, the performance of the cognitive radio system is evaluated by defining different values of the false alarm probabilities. In this case, even if PU_i is absent and channel CH_i is available to SU for communication, it is not detected and *SU1* resumes the communication with *SU2* over CH_u by using an underlay channel access scheme. This causes degradation in the performance of the system with an increase in the false alarm probability value. The effect of the different false alarm probability values on the performance of the system is reflected through the bar plot as shown in the Fig. 5. The associated numerical values are depicted in Table 3. For e.g. the throughput of the system with $P_f = 0\%$ is 44.08 Mbps, whereas with $P_f = 60\%$ the throughput of the system is 40.90 Mbps. In all of the cases considered here, it is assumed that channel CH_i is available with 80 % probability i.e. 80 % transmission is over CH_i and 20 % transmission is over CH_u. The false alarm probability reduces the opportunities to *SU1* for transmission over CH_i in spite of its availability due to imperfect spectrum sensing. This eventually results in the downfall of the performance of the system. This analysis reflects the importance of the accuracy in the channel sensing and channel selection algorithms.

Table-II: Throughput-Mean-Average-Power

Channel	Channel detection probabilities (%)		Throughput (Mbps)	P_{mavg_t} (W)
	P_{di}	P_{du}		
CH_u	0	100	38.64	0.89
CH_{iu}	20	80	40.90	1.04
CH_{iu}	40	60	44.08	1.22
CH_{iu}	60	40	47.13	1.42
CH_{iu}	80	20	50.10	1.55
CH_i	100	0	53.58	1.75

Table-III Throughput-Mean-Average-Power in the case of false alarm

Probability of the false alarm (P_f) %	Throughput (Mbps)	P_{mavg_t} (W)
0	50.10	1.56
20	47.13	1.40
40	44.08	1.22
60	40.90	1.04
80	38.64	0,89

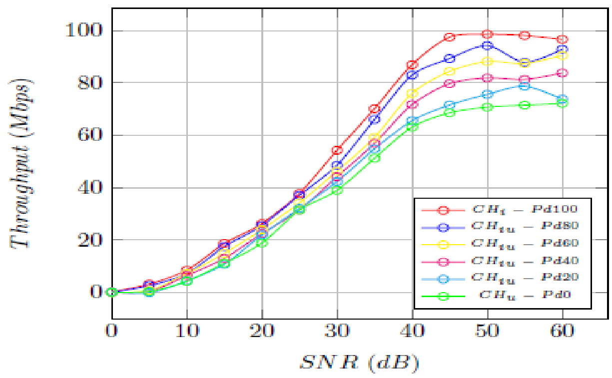

Fig.3. Throughput v/s SNR with perfect spectru sensing ($P_f = 0\%$)

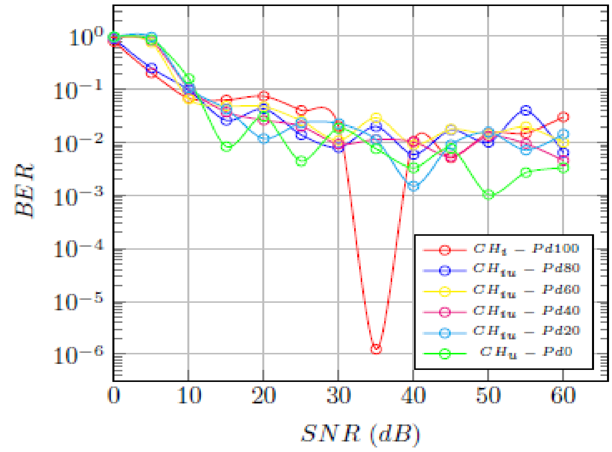

Fig.4. BER v/s SNR with perfect spectrum sensing

($P_f = 0\%$)

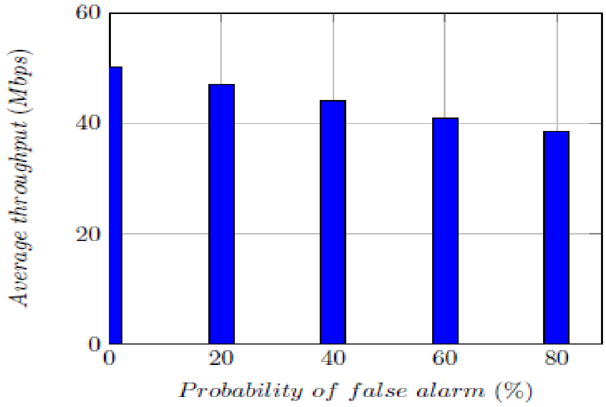

Fig.5. Average throughput v/s probability of the false alarm with imperfect spectrum sensing ($P_f \neq 0\%$)

V. CONCLUSION

The performance of the MIMO-OFDM adaptive cognitive radio system with the proposed hybrid (interweave-underlay) channel access scheme is analyzed and compared with the conventional underlay channel access scheme.

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The performance is evaluated under the constraint of the targeted BER and the maximum average transmission power. The performance is investigated for perfect spectrum sensing conditions (i.e. $P_f = 0\%$) with different channel true detection probabilities P_{di}. It has been observed that the throughput of the system shows significant improvement with the increase in the high-quality channel detection probability. This signifies that more the opportunities of the transmission over the high-quality channel or more the time span of the availability of the high-quality channel better will be the performance of the system. The use of the power adaptation scheme improves the energy efficiency of the system. To realize the importance of the channel sensing time, the accuracy of the channel sensing and channel detection algorithms, we have investigated the performance of the system under imperfect spectrum sensing condition. The performance is analyzed with different false alarm probability values. It is evident from the results obtained that as the probability of the false alarm increases there is a significant degradation in the performance of the system. The system is analyzed by considering the binary stochastic process to model the activities of the PUs. It can be useful to consider the different random distribution processes to model the activities of the PUs. The proposed scheme can be extended to a system comprising multiple PUs and SUs. The hybrid channel access scheme is useful in co-operative cognitive radio networks consisting of multiple SUs that act as relaying nodes to improve the performance of the entire network. Thus, the hybrid (interweave-underlay) channel access scheme can be exploited as one of the techniques to enhance the performance of the cognitive radio system. The proposed scheme can be used to optimize the performance of the cognitive WLAN, WRAN systems in the CR network.

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