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# Performance analysis of high-traffic cognitive radio communication system using hybrid spectrum access, prediction and monitoring techniques

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**Abstract** In this paper, the hybrid spectrum access and prediction techniques are exploited simultaneously in the high-traffic cognitive radio communication system, in order to enhance the throughput and overcome the problem of waiting states. The hybrid spectrum access is responsible for throughput enhancement by escaping the waiting states whereas the spectrum prediction alleviates the sensing errors in the high-traffic communication environment. The closed-form expression for the throughput of cognitive user (CU) communication is derived and validated the proposed approach with the reported literature. Moreover, a new framework is proposed to conquer the sharing issues of conventional and proposed approaches. In addition to this, the performance metrics of proposed framework such as the data-loss, energy-loss of the CU and interference at the PU have been analyzed.

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**Keywords** Cognitive Radio · Hybrid spectrum access · Spectrum monitoring · Spectrum prediction · Throughput

## 1 Introduction

Recently, an exponentially increasing demand of the spectrum due to explosion of the internet and multimedia services as well as its underutilization have led to the problem of spectrum scarcity [1, 2]. The potential solution of this problem is the dynamic spectrum access (DSA) or cognitive radio (CR) technology [1, 3–5], in which the unlicensed/secondary/cognitive user (CU) exploits the underutilized bands of the spectrum. The cognitive radio (CR) is an emerging intelligent technology which senses its environment and accesses the band of the PU, and transmit the data if it is idle at particular time or space, otherwise it waits or selects other channel for sensing [4]. However, the spectrum accessing techniques are responsible for sufficient protection of PU communication from the interference caused by the cognitive radio users [6].

The spectrum accessing techniques are broadly classified as follows: (1) Interweave, (2) Underlay, (3) Overlay and (4) Hybrid as illustrated in [6–8]. The hybrid spectrum access strategy is an advance technique which exploits the interweave and underlay techniques, simultaneously. Therefore, various researchers have explored the hybrid spectrum accessing strategy in order to improve the spectral efficiency [6, 8] and throughput [7]. In the hybrid spectrum accessing strategy, the CU senses the spectrum/channel and transmits data with full-power if the channel is idle otherwise with constrained power to protect the PU communication from interference caused by the cognitive radio users. As it is well apparent that the spectrum sensing plays a prominent role, therefore its performance should be high. The performance metrics of spectrum sensing technique are the probability of detection ($P_d$) and probability of false alarm ($P_f$) [9] where the values of $P_d$ and $P_f$ must be high and low respectively. However, the sensing time need to be significantly large for high value of $P_d$ and low value of $P_f$ as illustrated in [10]. As the sensing time and transmission time are inversely proportional to each other, therefore, various researchers have modified this relation by introducing advanced frame structures to maximize the throughput and sensing reliability [11, 12].

The PU channels are highly utilized in the high traffic cognitive radio networks (CRNs) which decreases the idle probability of the channels. However, the CU selects the channels for sensing randomly which causes the high probability of active sensing of channels and reduces the throughput drastically [13]. The significant loss of throughput in high traffic cognitive radio networks affects the performance parameters such as increase in the energy consumption and operating time which are explored in [14, 15]. Pei et al. [14] have illustrated an energy efficient design of sequential channel sensing and have optimized the power allocation, sensing time and sensing order to enhance the throughput of the CU. The throughput maximization problem under the single constraint on the sensing reliability has been presented in [15] i.e. sensing–throughput trade-off. To overcome the sensing- throughput trade-off, a new frame structure has been proposed by Stolas and Nallanathan [16], in which the sensing and transmission are considered as a parallel phenomenon. However, the limitation of this approach is the high data loss, therefore to reduce the data loss, the authors have proposed an improved frame structure discussed in [9].

In the recent years, a technique of spectrum prediction on the bases of historical information in order to forecast the channel states is in fashion [17–19]. In [17], the authors have presented a survey on the spectrum prediction techniques. Various spectrum prediction techniques such as hidden-Markov-model (HMM) based, multi-layer-perceptron (MLP) neural-network-based etc. are illustrated in literature [17]. As the practical point of view, each technique has certain error probabilities therefore, in the proposed study we have emphasized on the error present prediction technique i.e. imperfect spectrum prediction. Critian and Moh [18] have proposed an advance low-interference channel states prediction algorithm (LICSPA) to alleviate the prediction errors and interferences at the PU. Also, it is reported that proposed algorithm reduces the interference at the PU up to 40% as compared to that of the conventional approach of prediction. The cooperation among CUs has been exploited to enhance the spectrum prediction performance in [19]. Moreover, the authors have investigated the performance of different prediction methods and fusion scenarios by exploiting the various traffic conditions of PUs for cooperative prediction, and reported that the prediction accuracy is also the function of PU's traffic intensity ($\rho$) and its rate of change. Furthermore, it is also illustrated that the cooperation among CU enhances the accuracy of prediction on the cost of increased complexity, therefore, there must be a trade-off among these two metrics. The primary objective of the prediction is to improve the sensing performance by sensing only the idle predicted channels and avoid the interference at PU. In order to consider the imperfect spectrum predictions in the high traffic cognitive radio network for throughput maximization, a new frame structure has been presented in [13]. In this, the time frame is divided into three phases that is the prediction phase, sensing phase and data transmission phase. In the prediction phase, the CU predicts the idle channels on the bases of previous information whereas in the sensing phase, the CU only senses the idle predicted channels. Moreover, in the data transmission phase, the CU transmits data only on the idle sensed channels whereas it needs to wait on the active sensed channels which formulate the problem of wait/switch/stop states.

- *Wait state*: If the PU is active in the sensing period, the CU needs to wait for the next frame to sense the other channels.
- *Switch state*: If the PU is sensed active during the data transmission period, the CU has to switch its transmission over other available channels.
- *Stop State*: If the PU is sensed active in the data transmission period, the CU needs to stop the communication when all other channels are busy.

However, the major limitations of the proposed frame structure reported in [13] are as follows: (1) wait state and (2) high data loss and interference at the PU, if the PU resumes communication in the data transmission period. The high data-loss and interference occurs because the CU unable to detect the emergence of the PU during data transmission period and continue its data transmission with interweaves approach, even in the presence of PU. However, if the CU becomes able to detect the emergence of the PU during data transmission period, the data transmission (using interweave approach) can be discontinue or can use underlay approach for data transmission. Thus, the data loss and interference at PU can be improved significantly. Therefore, the author's main contributions to resolve the afore-mentioned potential issues are summarized as follows:

- In order to avoid the problem of wait states, we have proposed a novel approach in which the hybrid spectrum access technique named as: Approach-1 is exploited in the same frame structure as reported in [13]. The proposed approach overcomes the challenges of wait state as well as enhances the throughput of high traffic CRN.

- Further, we have exploited the concept of spectrum monitoring during data transmission period to alleviate the data loss of the CU and interference at the PU, named as Approach-2.

The remainder of the paper is organized as follows. The related work is presented in the Sect. 2. In Sect. 3, the system models for the two proposed approaches are described. The performance analysis of the proposed models is illustrated in the Sect. 4. In Sect. 5, the simulation results and analysis is presented and finally, the Sect. 6 concludes the work.

## 2 Related work

### 2.1 Evolution of frame structures

The typical frame structure for cognitive radio communication consists of two phases: (1) sensing phase and (2) transmission phase as shown in Fig. 1(a). The sensing time ($\tau_s$) is used to sense the channel and rest of the time ($T - \tau_s$) is used for the data transmission. The CU follows the same steps in each time frame i.e. once new frame has started, the CU starts from first step irrespective of the previous frame. However, the key drawback of this structure is the sensing-throughput trade-off as discussed in [15]. In [16], the authors have proposed a novel framework to overcome this limitation, in which the sensing and transmission are parallel phenomenon. The sensing information achieved at $N$th frame is used for the data transmission at $(N + 1)$th frame as shown in Fig. 1(b) [11]. However, the limitation of this approach is the out-dated sensing information. The CU is unable to adapt power according to the current sensing information, therefore the whole data of colliding frame get lost. To overcome this problem, the authors have proposed a new architecture as discussed in [9] in which the frame is divided into two or more blocks and each block comprises of two sub-blocks, explicitly, header-overhead and data-payload. Moreover, the header-overhead comprise of flag-bit which uses the sensing information of same frame that is computed up to to the starting time of particular, header-overhead block. In addition to this, the flag-bit is set if sensing result differs from the previous frame's sensing results. Thakur et al. [12] have proposed new frame structures for hybrid spectrum access technique in order to enhance the throughput and reduce the data loss.

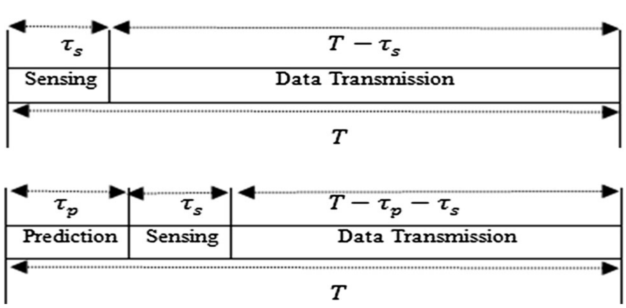


**Fig. 1** Frame structures in cognitive radio communication **a** conventional **b** using prediction slot [13]

### 2.2 Spectrum access strategies

The spectrum access plays a vital role in the cognitive radio communication systems therefore, various researchers have exploited the spectrum access techniques and classified as interweave, underlay, overlay and hybrid [6–8, 20–22]. The interweave strategy is the conventional accessing technique in which CU senses its environment and establishes communication only on the sensed idle channels and the spectrum sensing is a must for this approach [20]. The major limitation of the interweave approach is that the CU needs to wait for the spectrum to be idle and needs to stop/switch the communication if PU resumes it. The solution for this problem is provided by the underlay spectrum access technique [21], in which the CU establishes communication by transmitting constrained power in order to protect the PU communication from the interference and this technique does not require sensing. The techniques used to protect the PU from the interference are beam forming, spread spectrum and power control, etc. [20]. However, the limitation of underlay technique is the limited channel capacity due to constrained power [7]. Similar to the underlay technique, the overlay technique also allows the CU and PU to exploit the spectrum, simultaneously with full-power, however the communication of each user (CU and PU) is protected by using advanced encoding techniques such as dirty paper coding [20]. However, the overlay technique shows high-degree of complexity due to use of encoding techniques and therefore, it is avoided to use. As the underlay and interweave techniques, individually, unable to exploit the spectrum effectively, therefore the hybrid spectrum access came into existence [6–8, 22]. In the hybrid spectrum access, the CU accesses the idle channels with full-power, whereas the active channels are accessed by constrained power to avoid the interference with the PU caused by CU communication. Sharma et al. [7] have proposed the hybrid approach and evaluate its performance for both the periodic sensing and simultaneous sensing/transmission schemes. In [8], the authors have analyzed the hybrid spectrum access strategy using double-threshold energy detection method to indentify the location of the PU. Chu et al. [22] have investigated the hybrid spectrum access strategy for the cooperative CRNs (CCRN) using amplify-forward relaying and in order to analyze its mechanism, a continuous time Markov-chain model is proposed.

### 2.3 Spectrum monitoring

A typical frame structure for the CRNs with spectrum prediction ability is presented in Fig. 1(b). The bottleneck criterion of this structure is the time critical nature of the prediction, sensing and data transmission, which need to perform individually at specific time slots that means it is almost impossible to perform two or more phenomenon simultaneously. Due to this, the CU becomes unable to detect the emergence of PU during data transmission period which formulates the problems of data loss of CU and interference to the PU. The potential approach to resolve this issue is the spectrum monitoring during the data transmission period. The spectrum monitoring is an emerging technique in the area of dynamic spectrum access, which enables the CU to detect the emergence of PU even in the data transmission phase as reported in [23–25].

In [23], the authors have explored the concept of spectrum monitoring in detail and have presented the potential approaches for it on the basis of receiver statistics such as receiver error count (REC). In this approach, the CU receives the data from transmitter and counts the error in the received packet, if PU resumes its data transmission, there will be degradation in the performance of the received signal, which results in large number of errors in the received packet. Thus, the event of increased number of errors is considered as the emergence of PU. Further, the authors have illustrated the effect of cooperation on the spectrum monitoring using two CUs. Ali and Hamouda [24] have proposed an energy ratio spectrum monitoring algorithm for orthogonal frequency division multiplexing (OFDM) and derived the expression for the detection probability and probability of false alarm for additive white Gaussian noise (AWGN) channels. Orooji et al. [25] have presented a novel decision statistic for spectrum monitoring by using REC and have analyzed the detection and false-alarm probabilities for the same.

## 3 System models

### 3.1 System model for Approach-1

A cognitive radio network comprise of a pair of transceivers within high traffic environment has been considered, which accesses the channel by using hybrid spectrum access technique. The PU network is assumed to be cellular network and the PU's activities on each channel are independent because these channels may belong to different networks. In case of the spectrum sensing, the binary hypotheses considered for the received signal $r(t)$ are $H_0$ and $H_1$, which confirms the absence and presence of the PU, respectively.

$$r(t) = \begin{cases} h.s(t) + w(t) & H_1, \\ w(t) & H_0 \end{cases}$$

where $h$ is the channel gain, $w(t)$ is the AWGN and $s(t)$ is the transmitted signal of the PU. To achieve the reliable sensing results in order to protect the PU, the sensing duration must be above to the threshold value defines in [26] as:

$$\tau_{s\min} = \frac{1}{\gamma^2 f_s}\left(Q^{-1}(P_f) - Q^{-1}(P_d)\sqrt{2\gamma+1}\right)$$

where $\gamma$ denotes the signal-to-noise ratio (SNR) of the CU signal (using interweave approach) at cognitive receiver and $f_s$ denotes the sampling frequency. The traffic of PU is considered as binary stochastic process, in which 0 and 1 represents the idle and active channel, respectively. Moreover, the average arrival and holding time of the PU are modeled as the Poisson distribution (with parameter $\lambda$) and Binomial distribution (with parameter $\mu$), respectively [27] because cellular network follows the same. Thus, the active channel probability: $P(H_1) = \mu/\lambda$ and the idle channel probability: $P(H_0) = (\lambda - \mu)/\lambda$. In the CRN, the probability of channel to be active is considered as traffic intensity $\rho$ that means $\rho = P(H_1) = \mu/\lambda$.

In the proposed frame structure for cognitive radio communication, the entire time frame ($T$) is divided into three phases: (1) prediction phase ($\tau_p$), (2) sensing phase ($\tau_s$), and (3) data transmission phase ($T - \tau_p - \tau_s$) as shown in Fig. 1(b). Here, the CU performs spectrum prediction on the $N$ number of channels on the bases of previous information and furthermore, it senses randomly selected channel among idle predicted channels. Moreover, the data is transmitted on the channel with full-power $P_1$ if it is sensed idle otherwise with constrained power $P_2$, where $P_1 > P_2$.

The received SNR at the CU receiver due to transmitted power $P_1$ and $P_2$ is denoted as $SNR_{s1}$ and $SNR_{s2}$, respectively. However, the SNR at CU receiver due to the primary transmitted power $P_p$ is denoted as $SNR_p$. The throughput of the CU is the total transmitted data per unit time consumed. There are four possible conditions for data transmission in each frame as shown in Table 1.

### 3.2 System model for Approach-2

The potential issues of conventional and proposed hybrid approaches are the data loss and interference at the PU receiver, and the fundamental cause is the inability of CU to detect the emergence of PU during the data transmission period as discussed in Sect. 2.3. Therefore, in order to resolve these issues, we have proposed a new frame structure by exploiting the concept of spectrum monitoring in the data transmission phase as shown in Fig. 2. The

**Table 1** The throughput of CU for different conditions

| True channel state | Sensing state | Throughput |
|---|---|---|
| 0 | 0 | $c_0 = \frac{T-\tau_p-\tau_s}{T} log_2(1 + SNR_{s1})$ |
| 1 | 0 | $c_1 = \frac{T-\tau_p-\tau_s}{T} log_2\left(1 + \frac{SNR_{s1}}{1+SNR_p}\right)$ |
| 0 | 1 | $c_2 = \frac{T-\tau_p-\tau_s}{T} log_2(1 + SNR_{s2})$ |
| 1 | 1 | $c_3 = \frac{T-\tau_p-\tau_s}{T} log_2\left(1 + \frac{SNR_{s2}}{1+SNR_p}\right)$ |

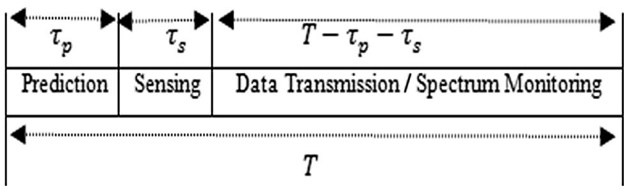


**Fig. 2** The proposed frame structure

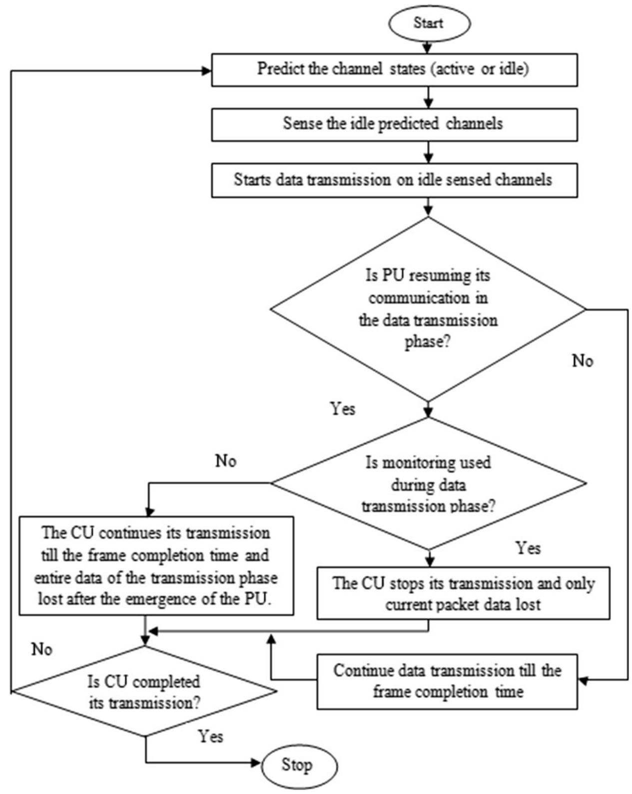


**Fig. 3** The flow-diagram of the proposed Approach-2

spectrum monitoring occurs at the CU receiver side parallel to the data reception by exploiting the received signal characteristics such as REC. Moreover, the CU receiver and transmitter are synchronized with each other on the control channel which is assumed to be always available [28]. In this scenario, we considered that a time frame consists of a number of data packets (*No*), where packet duration and packet energy is denoted as *PT* and *PE,* respectively.

The proposed frame structure is very similar to the structure shown in Fig. 1(b) however, in this, the CU needs to perform the data transmission and spectrum monitoring, simultaneously. In addition, the flow diagram of proposed approach is also illustrated in Fig. 3. The entire process of the proposed approach is as follows. Initially, the CU predicts the states of the channel whether active or idle and senses only the idle predicted channels. After that the CU starts data transmission on the idle sensed channels and there is the possibility that the PU resume its communication in the data transmission phase. If it happens, then in the conventional approach, the CU continues its transmission till the frame completion time which results the full-data loss of the CU after the emergence of PU, and the PU gets interference from the CU transmitted data. However, if we employ the spectrum monitoring technique in the data transmission phase, the CU stops its communication immediately and only the particular data packet at the emergence of PU gets lost. Moreover, the interference at PU receiver is avoided by stopping the CU transmission, due to detection of PU. Further, if the CU completed its data transmission then it stops its transmission otherwise, go back to the prediction phase in the next time frame.

## 4 Performance analysis

### 4.1 Throughput analysis using Approach-1

The very first step in the considered CRN is the spectrum prediction which is a binary hypothesis and the probability of wrong prediction ($P_{pe}$) is used to consider the imperfect spectrum prediction. In order to consider the true (actual, real) channel states (TCS) as active or idle, the probability distribution of true channel and predicted state is presented in Table 2. Therefore, the probabality of channel to be predicted idle is:

$$P_p^0 = \left(1 - P_{pe}\right)P(H_0) + P_{pe}P(H_1) \tag{1}$$

and the probability of channel to be predicted active is:

$$P_p^1 = \left(1 - P_{pe}\right)P(H_1) + P_{pe}P(H_0) \tag{2}$$

The next step after spectrum prediction is the spectrum sensing in which, the CU senses the idle predicted channels randomly. Here, we consider $k$ number of channels predicted to be idle among $N$ number of channels, therefore this event is similar to $k$ repeated Bernoulli trials ($k < N$), and corresponding probability is defined as: $C_N^k \left(P_p^0\right)^k \left(P_p^1\right)^{(N-k)}$. Therefore the probability of idle prediction for the entire CRN is given as:

**Table 2** The probability distribution of true and predicted channel states

| Prediction state (PS) | True channel state (TCS) | Probability |
|---|---|---|
| 0 | 0 | $(1 - P_{pe})P(H_0)$ |
| 0 | 1 | $P_{pe}P(H_1)$ |
| 1 | 0 | $P_{pe}P(H_0)$ |
| 1 | 1 | $(1 - P_{pe})P(H_1)$ |

$$P_N^0 = \sum_{k=1}^{N} C_N^k \left(P_p^0\right)^k \left(P_p^1\right)^{(N-k)} \tag{3}$$

and the probability of active prediction for whole CRN is provided by:

$$P_N^1 = C_N^0 \left(P_p^0\right)^0 \left(P_p^1\right)^{(N-0)} = \left(P_p^1\right)^N \tag{4}$$

The $P_N^1$ is the probabality that all channels in the CRN are active therefore, the CU randomly selects the channel for sensing, and the probability distribution regarding true channel and sensing states in provided in Table 3. However, the prediction and sensing phenominon are independent to each other. In addition, for the CU prediction, sensing and true channel states are also independent, therefore there will be eight possible combinations of probabality denoted as $\mathrm{P}_1, \mathrm{P}_2, \mathrm{P}_3 \ldots \mathrm{P}_8$ as shown in Table 4. Now, the throughput computation of CU network depends on the sensing state, which means the CU transmitt with full-power at idle sensed state while with constrained power on active sensed states. Therefore, by considering all possible combination in Table 4, the throughput of the CU is given as:

$$R_{avg} = (\mathrm{P}_1 + \mathrm{P}_3)c_0 + (\mathrm{P}_5 + \mathrm{P}_7)c_1 + (\mathrm{P}_2 + \mathrm{P}_4)c_2 + (\mathrm{P}_6 + \mathrm{P}_8)c_3 \tag{5}$$

However, the throughput varies with change in number of channels ($N$), therefore we need to normalize the throughput. It is evident that if the data is transmitted on the entire frame, the CU will achieve maximim throughput which is given as:

$$R_{up} = P(H_0)c_0 + P(H_1)c_1 \tag{6}$$

Now using Eq. (6), the computed normalized throughput is defiend as:

**Table 3** The probability distribution of true and sensing channel states

| Sensing state (SS) | True channel state (TCS) | Probability |
|---|---|---|
| 0 | 0 | $(1 - P_f)$ |
| 0 | 1 | $(1 - P_d)$ |
| 1 | 0 | $(P_f)$ |
| 1 | 1 | $(P_d)$ |

**Table 4** The probability distribution of the combination of true channel, prediction and sensing states

| T.C.S | P.S | S.S. | Probability |
|---|---|---|---|
| 0 | 0 | 0 | $\mathrm{P}_1 = (1 - P_f)P(H_0)(1 - P_{pe})\frac{P_N^0}{P_p^0}$ |
| 0 | 0 | 1 | $\mathrm{P}_2 = (P_f)P(H_0)(1 - P_{pe})\frac{P_N^0}{P_p^0}$ |
| 0 | 1 | 0 | $\mathrm{P}_3 = (1 - P_f)P(H_0)(P_{pe})\frac{P_N^1}{P_p^1}$ |
| 0 | 1 | 1 | $\mathrm{P}_4 = (P_f)P(H_0)(P_{pe})\frac{P_N^1}{P_p^1}$ |
| 1 | 0 | 0 | $\mathrm{P}_5 = (1 - P_d)P(H_1)(P_{pe})\frac{P_N^0}{P_p^0}$ |
| 1 | 0 | 1 | $\mathrm{P}_6 = (P_d)P(H_1)(P_{pe})\frac{P_N^0}{P_p^0}$ |
| 1 | 1 | 0 | $\mathrm{P}_7 = (1 - P_d)P(H_1)(1 - P_{pe})\frac{P_N^1}{P_p^1}$ |
| 1 | 1 | 1 | $\mathrm{P}_8 = (P_d)P(H_1)(1 - P_{pe})\frac{P_N^1}{P_p^1}$ |

$$R_{norm} = \frac{R_{avg}}{R_{up}} \tag{7}$$

Conventianlly, before designing a receiver, the value of $P_f$, $P_d$, and $\tau_s$ are already defined and in proposed CRN these are considered as invariable quantities. Therefore, the throughput of the CRN is affected by three parameters, i.e. the traffic intensity ($\rho$), probabality of wrong prediction ($P_{pe}$), and number of channels ($N$).

### 4.2 Analysis of performance metrics of the Approach-2

To analyze the performance of proposed Approach-2, we have considered three metrics, namely: (1) data loss of the CU ($RL$), (2) energy loss of the CU ($EL$), and (3) Signal-to-noise ratio (SNR) at the PU receiver. The data loss is in the form packet whereas the energy loss in the form of packet energy ($PE$). The data loss of the conventional approach ($RL_{Conven}$) is proportional to the traffic intensity i.e.$\{RL_{conven} = \rho \times No\}$ and the normalized value of the $RL_{Conven}$ is denoted as $RL_{norm\text{-}Conven}$ and defined as: $\{RL_{norm\text{-}Conven} = (\rho \times No)/\rho\}$. However, the data loss in the proposed approach ($RL_{Prop}$) is the particular packet on the emergence of PU. The normalized value of the $RL_{Prop}$ is denoted as $RL_{norm\text{-}Prop}$ where $RL_{norm\text{-}Prop} = 1/No$.

Similarly, the energy loss for the conventional and proposed approach is defined as $EL_{Conven} = \rho \times PE \times No$ and $EL_{Prop} = PE$ respectively. The normalized values of both is $\{EL_{norm-Conven} = (\rho \times PE \times No)/(PE \times No) = \rho\}$ and $\{EL_{norm-Prop} = PE/(PE \times No) = 1/No\}$.

The SNR at the PU receiver due to primary and cognitive transmission is denoted as $SNRP_p$ and $SNRP_s$, respectively. Therefore, the total SNR at the PU receiver due to PU and CU transmission is $SNRP_{ps} = SNRP_p/$

$(1 + SNRP_s)$. In the conventional approach, all the packets after the emergence of the PU get lost however, the particular packet at the emergence of PU lost in the proposed approach. The starting time ($PT_s$) and ending time ($PT_E$) of that packet depends on the traffic intensity ($\rho$) of the PU and computed as:

$$PT_s = \{(1-\rho) \times (T - (T_s + T_p))\} + \{(T_s + T_p)\}$$

$$PT_E = PT + PT_s$$

where $PT$ is the packet duration and defined as: $PT = (T - T_s - T_p)/No$. To compute the SNR at the PU receiver an algorithm is presented below as Algorithm-1.

---

**Algorithm- 1:** SNR calculation at PU receiver

**Input** $(T, \rho, T_s, T_p, PT)$

**Output** $(SNRP_{conven}, SNRP_{prop})$

**BEGIN**

**Step-1:** ***Variable Declaration***

$T$ : Frame Duration;
t = 0: 0.1: *T;*
$\rho$ : Traffic intensity;
$T_p$: Prediction duration
$T_s$: Sensing duration
$No$: Number of packets in data transmission phase.
$SNRP_s$: SNR at PU receiver due to cognitive transmission;
$SNRP_p$: SNR at PU receiver due to primary transmission;

**Step-2:** ***Computation of*** $PT, PT_s, PT_E$ ***and*** $SNRP_{ps}$,

$$PT \leftarrow \left\{\frac{T - T_s - T_p}{No}\right\}$$

$$PT_s \leftarrow \{(1-\rho) \times (T - (T_s + T_p))\} + \{(T_s + T_p)\};$$

$$PT_E \leftarrow \{PT_s + PT\};$$

$$SNRP_{ps} \leftarrow \frac{SNRP_p}{1 + SNRP_s}$$

**Step-3:** ***SNR calculations at the PU receiver using conventional and proposed approaches***

**for** $ii \leftarrow 1: length(t)$
  **If** $(t(ii) \le PT_s)$ **then**
    $SNRP_{conven}(ii) \leftarrow 0$
    $SNRP_{prop}(ii) \leftarrow 0$
  **elseif** $\{(t(ii) \ge PT_s) \&\& (t(ii) \le , PT_E)\}$ **then**
    $SNRP_{conven}(ii) \leftarrow SNRP_{ps}$
    $SNRP_{prop}(ii) \leftarrow SNRP_{ps}$
  **elseif** $(t(ii) \ge PT_E))$ **then**
    $SNRP_{conven}(ii) \leftarrow SNRP_{ps}$
    $SNRP_{prop}(ii) \leftarrow SNRP_p$
  **end**
 **end**
**end**

**END**

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## 5 Results and discussion

### 5.1 Proposed Approach-1

The numerically simulated throughput of the proposed Approach-1 in the CRN is presented and compared with the conventional approach reported in [13]. In [13], the authors have used the interweave spectrum access technique, which have introduces the problem of waiting probability. Due to this, the CU unable to transmit on the active sensed channels and total throughput is given as:

$$R_{avgc} = (P_1 + P_3)c_0 + (P_5 + P_7)c_1 \quad (8)$$

and normalized throughput in this case is:

$$R_{normc} = (R_{avgc}/R_{up}) \quad (9)$$

In the numerically simulated results, the conventional approach in [13] is denoted as Conv where as proposed approach as Hybrid. Moreover, the values of simulation parameters are selected on the bases of IEEE802.22 wireless regional area network (WRAN) standard and are presenetd in the Table 5.

The relation between normalized throughput and probability of wrong prediction for different values of traffic intensity in the conventional and proposed hybrid approach is presented in Fig. 4. It is illustrated that the normalized throughput decreases slowly for small values of wrong prediction whereas for large values it goes down rapidly. Moreover, the proposed hybrid approach outperforms the conventional approach, especially, for large values of the traffic intensity. The Fig. 5 illustrates the relation between the normalized throughput and traffic intensity for various values of the probability of wrong prediction and it is apparent that the throughput decreases (rapidly and slowly for high and low values of $P_{pe}$ respectively) with increase of the traffic intensity.

The impact of change in number of channels on the normalized throughput for several values of the traffic intensity is presented in the Fig. 6. Consequently, for large values of the traffic intensity (0.7, 0.9), the normalized throughput is directly proportional to the number of

**Table 5** The simulation parameters for the proposed CRN

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| $T$ | 100 ms | $f_s$ | 1500 samples/s |
| $\tau_p$ | 5 ms | $SNR_{s1}$ | 20 dB |
| $\tau_s$ | 2.5 ms | $SNR_{s2}$ | −5 dB |
| $P_d$ | 0.9 | $SNR_p$ | −15 dB |
| $P_f$ | 0.1 | $SNRP_s$ | 5 dB |
| $No$ | 10 | $SNRP_p$ | 15 dB |
| $PE$ | 1 mw | | |

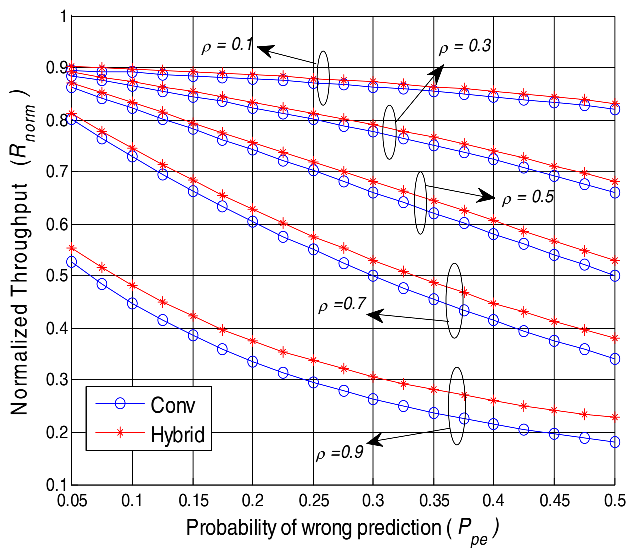


Fig. 4 Normalized throughput versus probability of wrong prediction for proposed hybrid and conventional approach ($N = 10$)

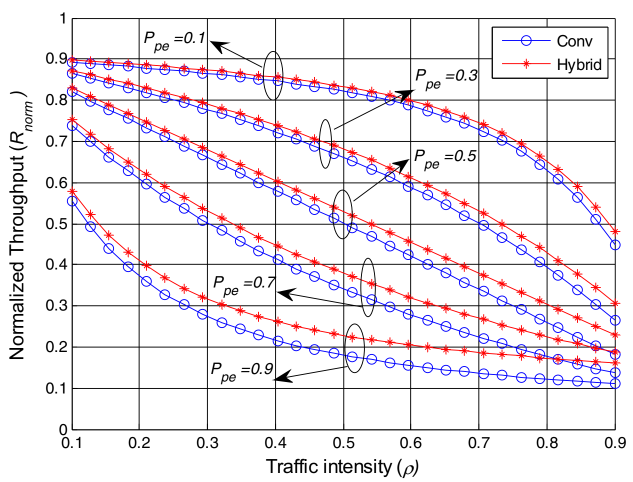


Fig. 5 Normalized throughput versus traffic intensity for proposed hybrid and conventional approach ($N = 10$)

channels. However, for low values of traffic intensity (0.1, 0.3), the normalized throughput increases for particular value of the number of channels and then becomes constant. Therefore, we conclude that there is a maximum limit for the number of channels needs to choose for maximum normalized throughput. From the above discussion, it is palpable that the proposed Approach-1 outperforms in the worst scenarios such as high traffic intensity as well as wrong predicted scenarios. In addition, the proposed approach provides enhanced throughput as compared to that of the conventional approach however, the proposed Approach-1 outperforms at high values of probability of wrong prediction.

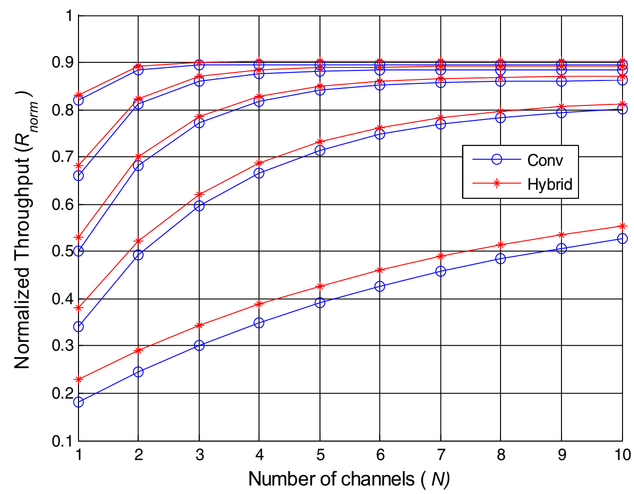


Fig. 6 Normalized throughput versus number of channels for proposed hybrid and conventional approach

## 5.2 Proposed Approach-2

In this scenario, the proposed Approach-1 and conventional approaches are assumed as conventional approach and denoted as Conven, and proposed Approach-2 as proposed approach and denoted as Prop. The three performance metrics, namely, the data, energy loss of the CU, and SNR at the PU receiver have been simulated and compared with the conventional approach. In this scenario, it is assumed that PU definitely resumes its communication during the data transmission period. The simulation parameters are same as in the Table 5.

In the Fig. 7, we have presented the relationship between the normalized data loss of the CU and traffic intensity of the PU for the conventional and proposed approach. It is apparent that, normalized data loss is increasing directly with increase of the traffic intensity for the conventional approach, however for the proposed approach, it is constant and is not affected by the traffic intensity because the particular packet lost on the emergence of PU whereas all the packets have lost after the emergence of PU in the conventional approach. The relation between normalized energy loss and traffic intensity in the conventional and proposed approaches have been illustrated in the Fig. 8. The normalized energy loss varies linearly with traffic intensity in the conventional approach whereas in the proposed approach it remains consistent. The cause behind this is that in the proposed approach particular data packet lost as we have stopped the communication on the emergence of PU, however in the conventional approach, the CU transmits continuously and get collided with PU after the emergence of the PU. Moreover, the relation between the SNR of the PU with time frame at

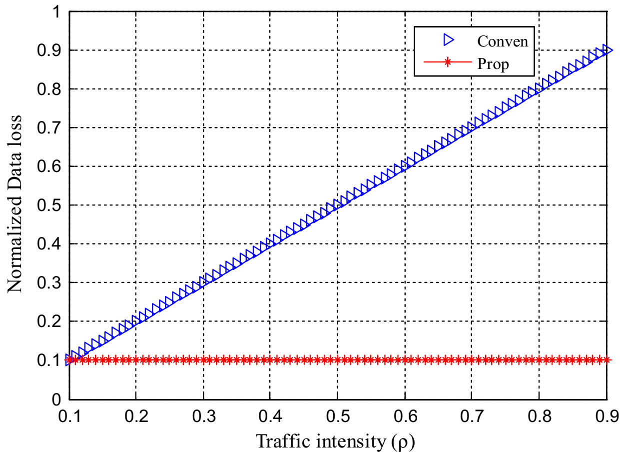


**Fig. 7** Normalized data loss of CU versus traffic intensity

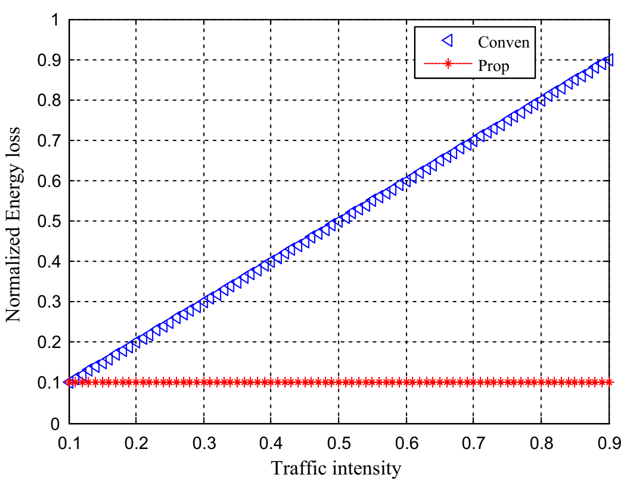


**Fig. 8** Normalized energy loss of CU versus traffic intensity

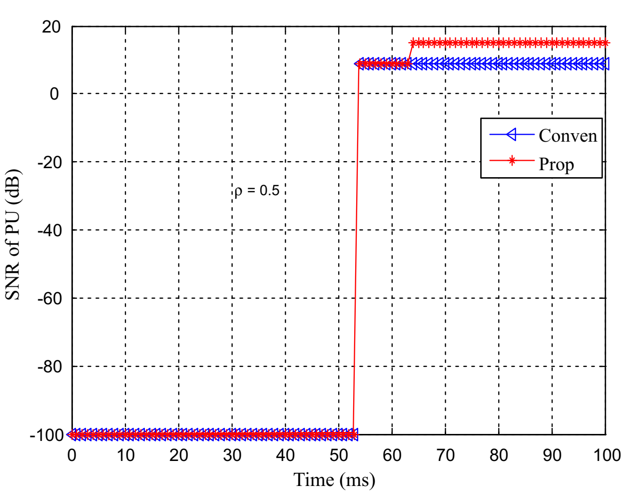


**Fig. 9** SNR at PU receiver versus time

particular value of traffic intensity ($\rho = 0.5$) is presented in the Fig. 9.

It is apparent that SNR remains zero till the emergence of the PU and have suddenly jumps to the value of $SNRP_{ps}$ in the conventional approach and remains constant till the end of the time frame, however, in the proposed approach SNR remains $SNRP_{ps}$ till the transmission of particular packet on the emergence of PU and after that it reaches to the full SNR (15 dB) i.e. $SNRP_p$ as the CU stops its transmission.

## 6 Conclusion

In this paper, we have exploited the concepts of spectrum prediction and hybrid spectrum access techniques in order to enhance the throughput by alleviating the spectrum sensing errors. Moreover, the problem of wait states is resolved by using hybrid spectrum access technique. We have presented the closed-form expression for the throughput of the proposed Approach-1 and have compared with conventional approach. The simulation results have confirmed that proposed Approach-1 outperforms the conventional approach in the worst scenarios such as very high traffic CRN and large prediction errors. In addition, by exploiting the shared issues of conventional and proposed Approach-1, we have presented a new frame structure and flow diagrams to resolve these issues. The performance of the proposed structures has analyzed using three metrics and have illustrated that proposed Approach-2 outperforms the Approach-1. The performance analysis of the Approach-2 by optimizing the various parameters will be reported in the future communication.

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