

Hybrid Spectrum Access Strategy for Throughput Enhancement of Cognitive Radio Network



Indu Bala, Kiran Ahuja, and Anand Nayyar

Abstract Recently, cognitive radio technology has gained worldwide attention due to its potential to overcome spectrum scarcity. The technology allows unlicensed users to use licensed spectrum in a manner such that minimum or no interference may be experienced by licensed users. To do so, the conventional scheme divides the time frame into two slots i.e. sensing slot and data transmission slot. In this scenario, the achievable throughput of unlicensed user fundamentally depends on the accuracy of sensing results since the sensing error in terms of miss detection and false alarm results into collision and spectrum underutilization, respectively. To overcome this bottleneck, an improved frame structure is proposed in this paper with two sensing slots and one data transmission slot. Based on the sensing results of the current and previous frame, the proposed scheme allows unlicensed users to switch between underlay and interweave mode of communication to enhance secondary user's throughput. It is shown that proposed scheme has a potential to achieve 50% more throughput as compare to the conventional schemes, when channel is occupied by primary user. The simulation results are presented to illustrate the effectiveness of the proposed scheme. Moreover, the performance of proposed scheme is also compared with the conventional schemes to validate the results.

Keywords Sensing · Hybrid spectrum access · Frame structure · Throughput · Data loss

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1 Introduction

From last few decades, we all have witnessed the tremendous growth in wireless communication that has increased the bandwidth requirement manifolds. However, with traditional spectrum allocation policies, it has become extremely difficult to assign spectrum for new services/applications. The traditional spectrum allocation policies in use provide spectrum access rights exclusively to the user who purchased the spectrum (known as primary user i.e. PU) for long term use. The unlicensed user (known as secondary user i.e. SU) is refrained from transmission in this channel even if it is not in use by PU. Thus, whole wireless industry is facing spectrum shortage to deploy new services/applications. On contrary to the spectrum scarcity issue, the recent FCC report has revealed that spectrum allocated for different services, is being used sporadically [1]. Thus, the existing spectrum scarcity problem is mainly due to the improper use of the spectrum rather than actual shortage of the spectrum. This fact has pushed regulatory authorities to explore the new communication paradigms to overcome spectrum scarcity issue. Recently, cognitive radio technology has evolved as the most promising technology with a potential to overcome this issue by allowing secondary users to utilize vacant or partial utilized spectrum whenever primary users are not using it [2]. Thus, the basic requirement of the technology is that SU should remain all time updated with the spectrum occupancy level by primary users through spectrum sensing. Many spectrum sensing techniques have been proposed for cognitive radio networks in this regard. However, due to the ease in implementation and no prior knowledge requirement about primary user, energy detection (ED) is most commonly used spectrum sensing scheme [3, 4]. The performance of the energy detector is measured in term of probability of detection (P_d) and probability of false alarm (P_f) and must be high and low, respectively. To meet these requirements, the spectrum sensing time must be high for the accurate detection of primary user in a channel. However, the main drawback with long sensing duration is that it reduces the data transmission time and therefore SU throughput also. To overcome this issue, many researchers have proposed solutions like parallel sensing and transmission [4], improvement in frame structures [5], hybrid spectrum access [6], threshold adaptation [7] and dedicated channel for spectrum sensing [8] etc. However, to our best knowledge, hybrid spectrum access scheme with improved frame structure has not been analyzed much to improve the secondary throughput. Therefore, a hybrid spectrum access scheme with an improved frame structure has been proposed in this paper, to enhance secondary user's throughput and to reduce the data loss due to sensing errors.

The rest of the paper is organized as follows: The dynamic spectrum access schemes are discussed in Sect. 2. The system model and frame structures are discussed in Sect. 3. In Sect. 4, the conventional and proposed spectrum access scheme is discussed and analytical expression for SU throughput, effective SU throughput and data loss have been derived. Simulation results are presented in Sect. 5 followed by conclusion in Sect. 6.

2 Dynamic Spectrum Access Schemes

The dynamic spectrum access is a mechanism to increase the spectrum efficiency by the real time adjustment of the radio resources [1]. It allows SUs to use licensed spectrum bands dynamically for transmission. Figure 1 illustrates various spectrum access schemes reported in literature [9–20].

Figure 2 shows various spectrum sharing paradigms for cognitive radio network (CRN). The underlay approach allows both PU and SU to transmit simultaneously over a same channel as long as the interference from SU to PU is below interference temperature [9]. Similar to the Ultra Wide Band (UWB) technology, this approach allows SU to spread its signal over a wide frequency range, and the signal level remains below noise level. Thus, the scheme is able to provide seamless connectivity and limited data rates for short range communication [10].

Similar to the underlay scheme, the overlay scheme also allow SUs to transmit over the licensed band along with PU such that the performance of PU may not be affected. The two main approaches used in this paradigm are (i) Channel coding, and (ii) network coding. In the channel coding approach PU transmits a packet that is known the SU. The SU splits its transmission power into two parts to transmit its own (SU) packet along with the PU packet such that the signal to interference and noise ratio (SINR) at PU receiver is not affected much. In addition to this, the SU transmitter can also exploit dirty paper coding to transmit the SU packet to cancel out the interference at SU receiver [11]. The network coding scheme allows SU to encode its packet onto the PU packet while relaying it. Thus, SU does not require

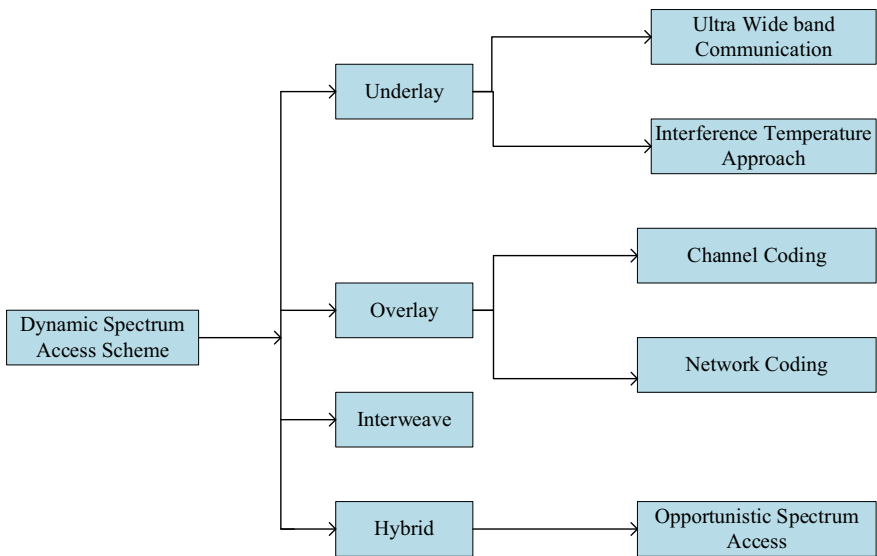


Fig. 1 Classification of spectrum access schemes

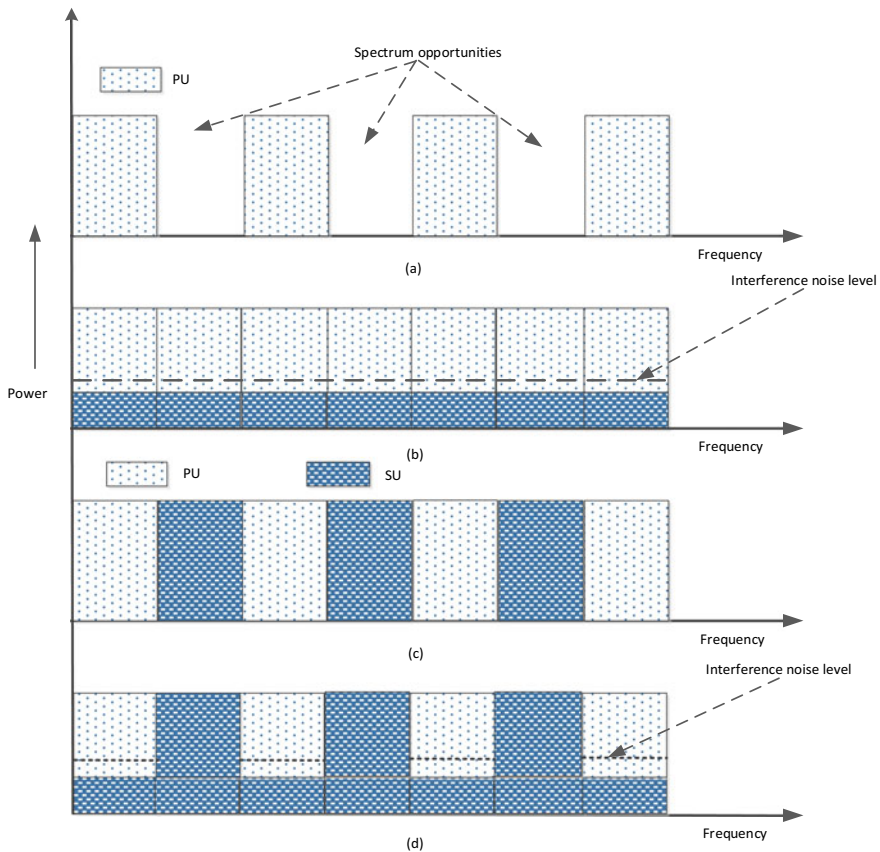


Fig. 2 Spectrum sharing paradigms **a** spectrum opportunities/holes. **b** Underlay paradigm. **c** Interweave paradigm. **d** Hybrid paradigm

separate spectrum access to transmit its own packets and therefore PU transmission remains unaffected [12].

On contrary to the previously discussed approaches, Interweave approach does not allow SU to transmit in licensed frequency band when PU is active on it. The spectrum sensing is mandatory to this approach and it is also known as opportunistic spectrum access (OSA) in a sense that SU can exploit the spectrum opportunities in time, space, and/or frequency domain [13]. In comparison to the underlay scheme, this scheme allows high transmission power level to support high data rates. However, the transmission is truncated abruptly on the emergence of PU in the channel. To overcome all these drawbacks, a hybrid spectrum access scheme is proposed in this paper that switches between interweave and underlay mode of communication based on the channel occupancy level by PU. The proposed scheme not only offers seamless connectivity but high data rates also. In addition to this, transmission frame structure is also improved to achieve high secondary throughput.

The main contributions of this paper are as follows:

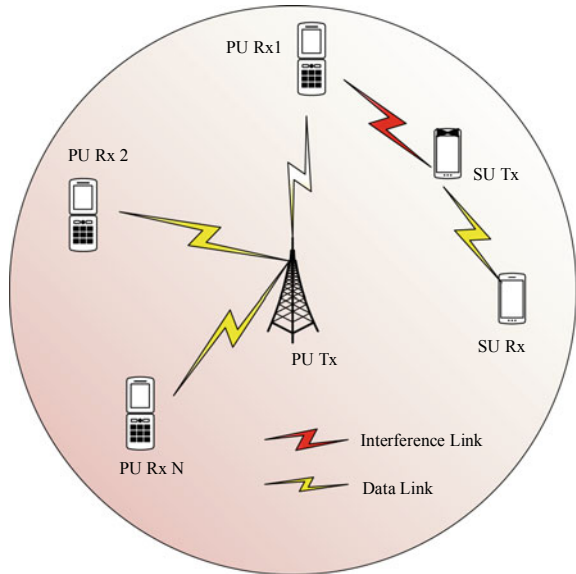
- (i) A hybrid spectrum access scheme is proposed with an improved frame structure to access idle channels using interweave approach and busy channels using underlay approach.
- (ii) The proposed scheme has a potential to overcome sensing errors with the help of two sensing slots.
- (iii) The analytical expressions for SU's effective throughput and data loss are derived for the proposed spectrum access schemes.

3 System Model and Frame Structure

3.1 System Model

Consider a communication scenario with one primary transmitter (PU Tx) that uses its allocated licensed frequency band to transmit information to the primary receiver (PU RxN) with power P_P as shown in Fig. 3. The secondary communication system comprises of SU Tx–SU Rx pair that shares the licensed frequency band with PU. The SU Tx is equipped with an energy detector that constantly monitors the channel variations to know the presence or absence of the PU in a licensed frequency band.

Fig. 3 Proposed communication system scenario



3.2 Frame Structure

For given communication scenario, the conventional schemes discussed in [3] and [5] divides time into equal sized frames, where each frame consists of two time slots: the sensing slot and the transmission slot as shown in Fig. 4a. According to this frame structure, SU senses for τ units of time to know PU presence/absence from the channel and decides for transmission/no transmission or mode of transmission for the remaining frame duration of $T - \tau$ units of time. Generally, there exists tradeoff between these two as excessive long sensing duration reduces the transmission time and short sensing duration may leads to the miss detection of PU. Both situations affect primary and secondary users adversely. Moreover, the spectrum sensing by the SU is assumed to be imperfect, and thus sensing errors (i.e., miss detection and false alarm) limits the SU throughput.

Figure 4b shows the proposed frame structure for hybrid spectrum access in which transmission frame is divided into three slots i.e. two sensing slots and one data transmission slot. The basic notion of adding second sensing slot is to enhance the accuracy of sensing results and thus to increase the secondary throughput. In this frame structure, the second sensing slot is optional and it depends on the sensing results of current and previous frame. For example, if the spectrum sensing results of

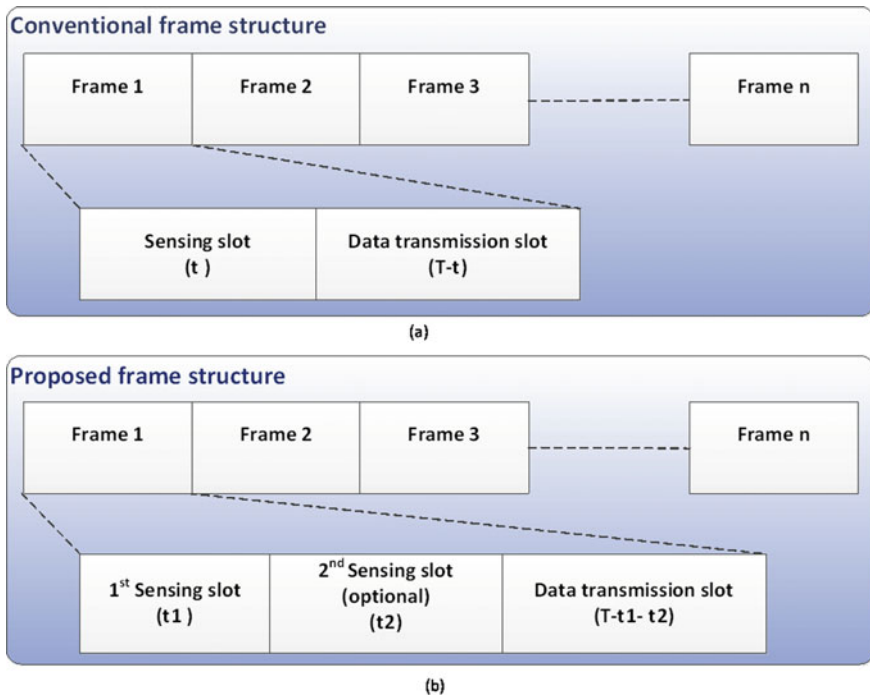


Fig. 4 a Conventional frame structure. b Proposed frame structure

current and previous frame are same, the secondary user performs spectrum sensing only once for the current frame. However, if the sensing results of the current frame are different from the previous frame, the SU will sense the channel again to avoid ambiguity in sensing results. In case of second sensing, the results of the second sensing slot will be considered final even if they are wrong.

4 Performance Analysis

In this section, we study the conventional and proposed spectrum sharing schemes in detail. The closed form of expression for effective throughput and data loss are derived for each scheme. For spectrum sharing scenario presented in Sect. 3, the sensing results of the received signal $r(t)$ by SU follows the binary hypothesis H_1 and H_0 to represents the presence and absence of the primary user, respectively.

$$r(t) = \begin{cases} h \cdot x(t) + w(t), & H_1 : \text{PU is present} \\ w(t), & H_0 : \text{PU is absent} \end{cases} \quad (1)$$

where, h , $x(t)$ and $w(t)$ represents channel gain, primary transmitted signal and additive white Gaussian noise (AWGN), respectively. The description of the parameters is given in Table 1.

Table 1 Parameters description [3, 5, 6]

S. No.	Parameter	Description
1	T	Total time frame
2	τ_1	Time duration of 1st sensing slot
3	τ_2	Time duration of 2nd sensing slot
4	$T - \tau_1$	Data transmission time with one sensing slot
5	$T - \tau_1 - \tau_2$	Data transmission time with two sensing slot
6	P_d	Probability of detection
7	P_f	Probability of false alarm
8	P_1	SU transmission power in Interweave mode
9	P_2	SU transmission power in Underlay mode
10	P_P	PU transmission power
11	N_p	Noise power at SU receiver
12	h_{ps}	Channel gain between PU Tx and SU Rx
13	h_{ss}	Channel gain between SU Tx and SU Rx
14	$P(H_0)$	Probability of channel being Idle
15	$P(H_1)$	Probability of channel being busy

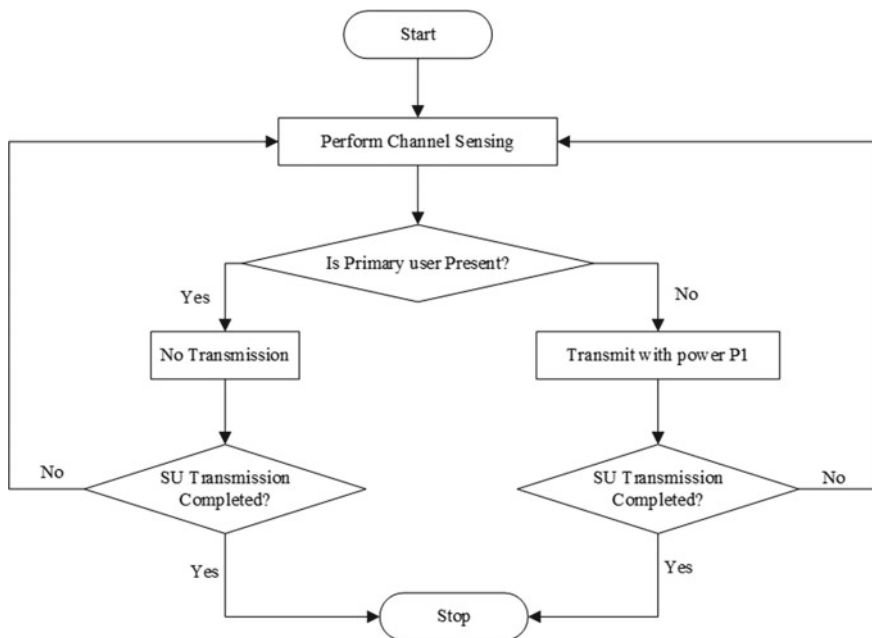


Fig. 5 Conventional spectrum access scheme with one sensing slot (Conv-I)

Figure 5 shows the conventional spectrum access approach with one sensing slot (Conv-I) in which sensing is done at the beginning of the frame. Based on the sensing results, four data transmission cases are possible (Refer Table 2).

Since SU is allowed to transmit with power P_1 whenever channel is sensed idle, the secondary user is allowed to transmit in case 1 and 2 as given in Table 2. Thus, SU throughput will be given by (2)

$$T P_1 = \frac{T - \tau}{T} [P(H_0)(1 - P_f)C_{00} + P(H_1)(1 - P_d)C_{01}] \quad (2)$$

Table 2 Data transmission scenarios for Conv-I scheme [3]

Sensing state	Actual state	Transmission type	Transmission duration	SNR	Capacity
Idle	Idle	Interweave	$T - \tau$	$\frac{P_1 h_{ss}}{N_p}$	C_{00}
Idle	Busy	Interweave	$T - \tau$	$\frac{P_1 h_{ss}}{N_p + P_p h_{ps}}$	C_{01}
Busy	Idle	No transmission	X	0	C_{10}
Busy	Busy	No transmission	X	0	C_{11}

Where, $C_{xx} = B \log_2(\text{SNR})$

where C_{xx} represents capacity with first subscript representing sensed state and second subscript representing actual channel state. However, the effective SU throughput is when SU is able to sense the channel accurately and decides the transmission power level accordingly. Under imperfect sensing situation, when SU is not able to sense PU n a channel and transmits using interweave mode, whole transmission results into data loss. Thus, the effect SU throughput and data loss for Conv-I scheme will be given by (3) and (4), respectively.

$$TP_1^E = \frac{T - \tau}{T} [P(H_0)(1 - P_f)C_{00}] \tag{3}$$

$$DL_1 = \frac{T - \tau}{T} [P(H_1)(1 - P_d)C_{01}] \tag{4}$$

Figure 6 shows conventional hybrid spectrum access scheme with one sensing slot (Hybrid-I) in which based on the sensing results, SU transmits with transmission power P_1 in interweave mode, when channel is idle and with transmission power P_2 in underlay mode when channel is busy. Based on this, four possible data transmission scenarios are given in Table 3.

The SU throughput, effective throughput and data loss for Hybrid-I scheme will be given by (5), (6) and (7), respectively.

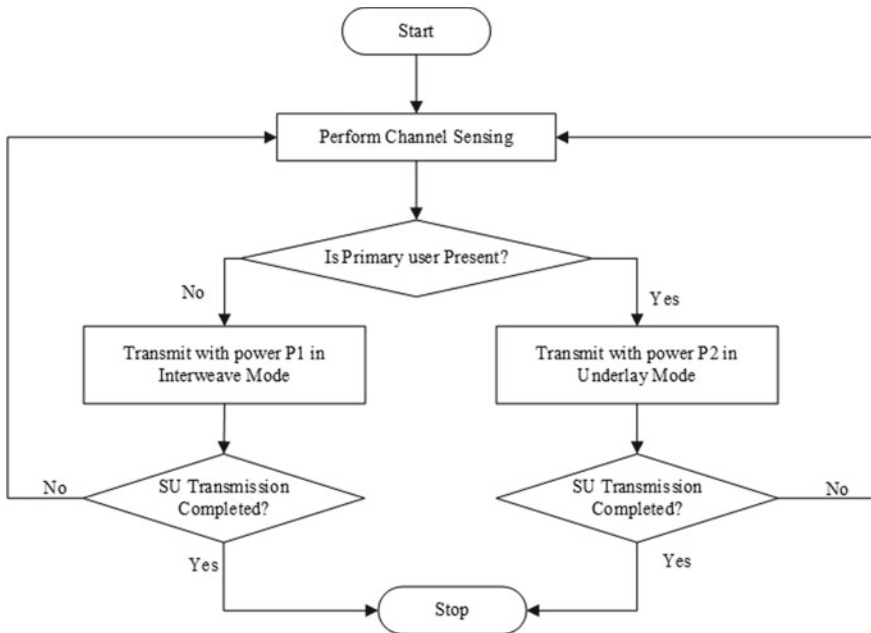


Fig. 6 Conventional hybrid spectrum access scheme single sensing slot (Hybrid-I) [6]

Table 3 Data transmission scenarios for hybrid-I scheme [6]

Sensing state	Actual state	Transmission type	Transmission duration	SNR	Capacity
Idle	Idle	Interweave	$T - \tau$	$\frac{P_1 h_{ss}}{N_p}$	C_{00}
Idle	Busy	Interweave	$T - \tau$	$\frac{P_1 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{01}
Busy	Idle	Underlay	$T - \tau$	$\frac{P_2 h_{ss}}{N_p}$	C_{10}
Busy	Busy	Underlay	$T - \tau$	$\frac{P_2 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{11}

Where, $C_{xx} = B \log_2(\text{SNR})$

$$T P_2 = \frac{T - \tau}{T} \left[P(H_0)(1 - P_f)C_{00} + P(H_1) \begin{matrix} (1 - P_d)C_{00}P(H_0)(P_f)C_{10} \\ + P(H_1)(P_d)C_{11} \end{matrix} \right] \quad (5)$$

$$T P_1^E = \frac{T - \tau}{T} [P(H_0)(1 - P_f)C_{00} + P(H_0)(P_f)C_{10} + P(H_1)(P_d)C_{11}] \quad (6)$$

$$DL_2 = \frac{T - \tau}{T} [P(H_1)(1 - P_d)C_{01}] \quad (7)$$

Figure 7 illustrate conventional spectrum access scheme with two sensing slots (Conv-II) in which sensing is performed once only if the sensing results of current and previous frame are same. In case the sensing results of current frame and previous frame are different, sensing is performed again to avoid ambiguity in sensing results. Based on this, twelve possible data transmission scenarios are given in Table 4.

The SU throughput, effective throughput and data loss for Conv-II scheme will be given by (8), (9) and (10), respectively

$$T P_3 = \frac{T - \tau_1}{T} [P(H_0)^2(1 - p_f^1)C_{000x} + P(H_1)P(H_0)(1 - p_d^1)C_{010x}]$$

$$+ \frac{T - \tau_1 - \tau_2}{T} \left[\begin{matrix} P(H_0)^2 p_f^1 (1 - p_f^2) C_{0010} \\ + P(H_0)P(H_1) p_d^1 (1 - p_d^2) C_{0110} \\ + P(H_1)P(H_0)(1 - p_f^1)(1 - p_f^2) C_{1000} \\ + P(H_1)P(H_1)(1 - p_d^1)(1 - p_d^2) C_{1100} \end{matrix} \right] \quad (8)$$

$$T P_1^E = \frac{T - \tau_1}{T} [P(H_0)^2(1 - p_f^1)C_{000x}]$$

$$+ \frac{T - \tau_1 - \tau_2}{T} \left[\begin{matrix} P(H_0)^2 p_f^1 (1 - p_f^2) C_{0010} \\ + P(H_1)P(H_0)(1 - p_f^1)(1 - p_f^2) C_{1000} \end{matrix} \right] \quad (9)$$

$$DL_3 = \frac{T - \tau_1}{T} [P(H_1)P(H_0)(1 - p_d^1)C_{010x}]$$

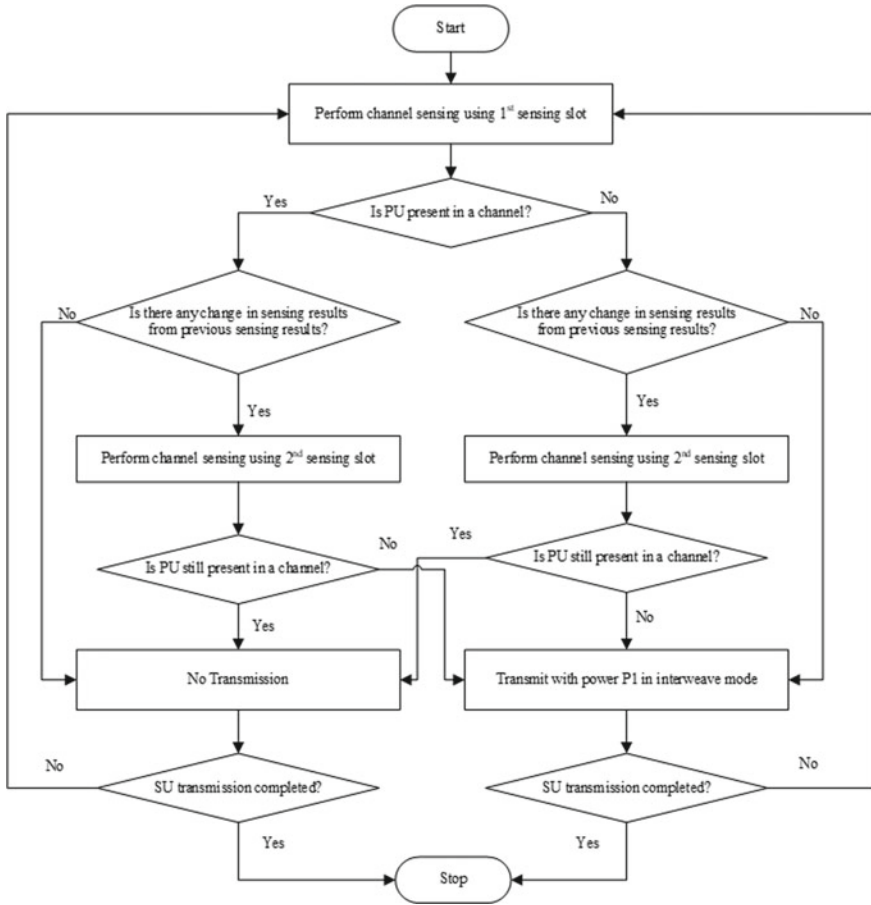


Fig. 7 Conventional spectrum access scheme with two sensing slots (Conv-II) [6]

$$+ \frac{T - \tau_1 - \tau_2}{T} \left[\begin{matrix} P(H_0)P(H_1)p_d^1(1 - p_d^2)C_{0110} \\ + P(H_1)P(H_0)(1 - p_f^1)(1 - p_f^2)C_{1100} \end{matrix} \right] \quad (10)$$

The term C_{xxxx} in (8), (9) and (10) represents capacity and first subscript represents sensing state of previous frame, second subscript represents sensing state of current frame, third subscript represents first sensing results and fourth subscript represents sensing results of second sensing.

Figure 8 shows the proposed hybrid spectrum access scheme in which the frame length is divided into three slots i.e. two sensing slots and a data transmission slot. However, unlike Conv-II scheme, the proposed scheme allows the SU to transmit in interweave mode with power P_1 on finding the channel idle and in underlay mode with power P_2 on finding channel busy. Based on the access behavior; twelve possible data transmission scenarios are enlisted in Table 5.

Table 4 Data transmission scenarios for Conv-II scheme [5]

Last state	Current state	1st sensing result	2nd sensing result	Tx type	Tx duration	SNR	Capacity
Idle	Idle	Idle	X	Interweave	$T - \tau_1$	$\frac{P_1 h_{ss}}{N_p}$	C_{000x}
Idle	Idle	Busy	Idle	Interweave	$T - \tau_1 - \tau_2$	$\frac{P_1 h_{ss}}{N_p}$	C_{0010}
Idle	Idle	Busy	Busy	Underlay	$T - \tau_1 - \tau_2$	0	C_{0011}
Idle	Busy	Idle	X	Interweave	$T - \tau_1$	$\frac{P_1 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{010x}
Idle	Busy	Busy	Idle	Interweave	$T - \tau_1 - \tau_2$	$\frac{P_1 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{0110}
Idle	Busy	Busy	Busy	Underlay	$T - \tau_1 - \tau_2$	0	C_{0111}
Busy	Idle	Idle	Idle	Interweave	$T - \tau_1 - \tau_2$	$\frac{P_1 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{1000}
Busy	Idle	Idle	Busy	Underlay	$T - \tau_1 - \tau_2$	0	C_{1001}
Busy	Idle	Busy	X	Underlay	$T - \tau_1$	0	C_{101x}
Busy	Busy	Idle	Idle	Interweave	$T - \tau_1 - \tau_2$	$\frac{P_1 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{1100}
Busy	Busy	Idle	Busy	Underlay	$T - \tau_1 - \tau_2$	0	C_{1101}
Busy	Busy	Busy	X	Underlay	$T - \tau_1$	0	C_{111x}

where, $C_{xxxx} = B \log_2(\text{SNR})$

Thus, the analytical expression for secondary throughput, effective SU throughput and data loss of the proposed scheme will be given by (11), (12) and (13), respectively.

$$\begin{aligned}
 TP_4 = & \frac{T - \tau_1}{T} \left[P(H_0)^2 (1 - p_f^1) C_{000x} + P(H_1) P(H_0) (1 - p_d^1) C_{010x} \right] \\
 & + P(H_1) P(H_0) (1 - p_d^1) C_{101x} + P(H_1)^2 (p_d^1) C_{111x} \\
 & + \frac{T - \tau_1 - \tau_2}{T} \left[\begin{aligned}
 & P(H_0)^2 p_f^1 (1 - p_f^2) C_{0010} + P(H_1) P(H_0) p_d^1 p_d^2 C_{0111} \\
 & + P(H_1)^2 (1 - p_d^1) (1 - p_d^2) C_{1100} + P(H_0)^2 p_f^1 p_f^2 C_{0011} \\
 & + P(H_1) P(H_0) p_d^1 (1 - p_d^2) C_{0110} + P(H_1) P(H_0) p_f^2 (1 - p_f^1) C_{1001} \\
 & + P(H_1)^2 (1 - p_d^1) p_d^2 C_{1101} + P(H_1) P(H_0) (1 - p_f^1) (1 - p_f^2) C_{1000}
 \end{aligned} \right] \quad (11)
 \end{aligned}$$

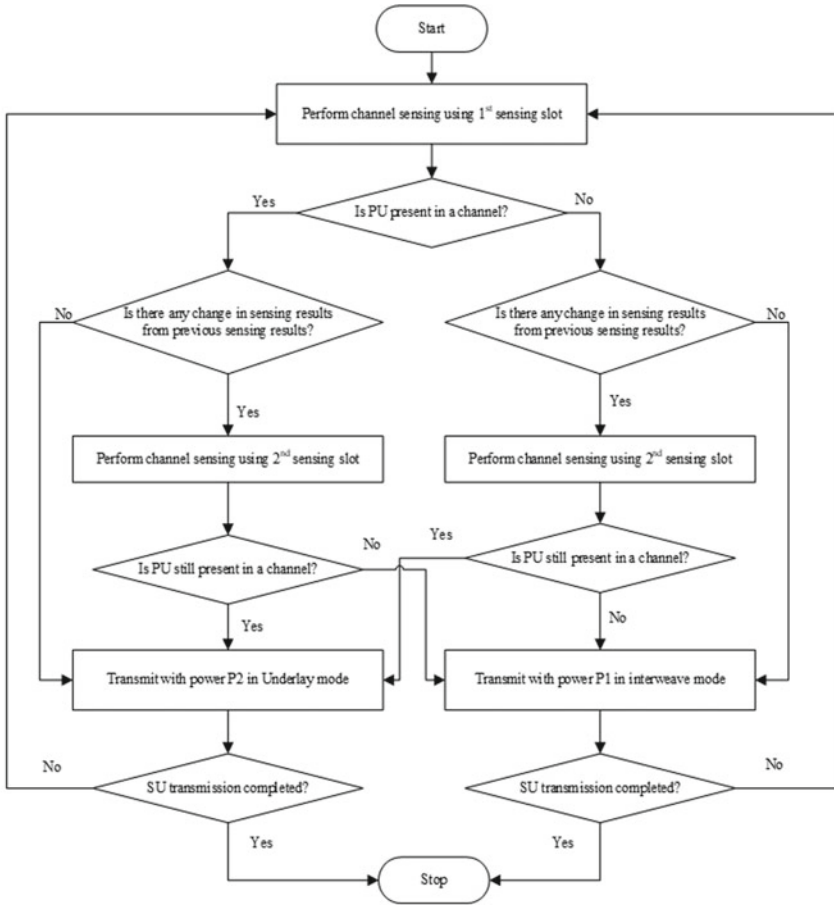


Fig. 8 Proposed hybrid spectrum access scheme with two sensing slots

$$\begin{aligned}
 TP_4^E = & \frac{T - \tau_1}{T} \left[P(H_0)^2(1 - p_f^1)C_{000x} + P(H_1)P(H_0)(1 - p_d^1)C_{101x} \right. \\
 & \left. + P(H_1)^2(p_d^1)C_{111x} \right] \\
 & + \frac{T - \tau_1 - \tau_2}{T} \left[P(H_0)^2 p_f^1(1 - p_f^2)C_{0010} \right. \\
 & \left. + P(H_1)P(H_0)p_d^1 p_d^2 C_{0111} + P(H_0)^2 p_f^1 p_f^2 C_{0011} \right. \\
 & \left. + P(H_1)P(H_0)p_f^2(1 - p_f^1)C_{1001} \right. \\
 & \left. + P(H_1)^2(1 - p_d^1)p_d^2 C_{1101} \right. \\
 & \left. + P(H_1)P(H_0)(1 - p_f^1)(1 - p_f^2)C_{1000} \right] \quad (12)
 \end{aligned}$$

Table 5 Data transmission scenarios (proposed approach)

Last state	Current state	1st sensing result	2nd sensing result	Tx type	Tx duration	SNR	Capacity
Idle	Idle	Idle	x	Interweave	$T - \tau_1$	$\frac{P_1 h_{ss}}{N_p}$	C_{000x}
Idle	Idle	Busy	Idle	Interweave	$T - \tau_1 - \tau_2$	$\frac{P_1 h_{ss}}{N_p}$	C_{0010}
Idle	Idle	Busy	Busy	Underlay	$T - \tau_1 - \tau_2$	0	C_{0011}
Idle	Busy	Idle	X	Interweave	$T - \tau_1$	$\frac{P_1 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{010x}
Idle	Busy	Busy	Idle	Interweave	$T - \tau_1 - \tau_2$	$\frac{P_1 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{0110}
Idle	Busy	Busy	Busy	Underlay	$T - \tau_1 - \tau_2$	0	C_{0111}
Busy	Idle	Idle	Idle	Interweave	$T - \tau_1 - \tau_2$	$\frac{P_1 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{1000}
Busy	Idle	Idle	Busy	Underlay	$T - \tau_1 - \tau_2$	0	C_{1001}
Busy	Idle	Busy	X	Underlay	$T - \tau_1$	0	C_{101x}
Busy	Busy	Idle	Idle	Interweave	$T - \tau_1 - \tau_2$	$\frac{P_1 h_{ss}}{N_p + P_p \cdot h_{ps}}$	C_{1100}
Busy	Busy	Idle	Busy	Underlay	$T - \tau_1 - \tau_2$	0	C_{1101}
Busy	Busy	Busy	X	Underlay	$T - \tau_1$	0	C_{111x}

where, $C_{xxx} = B \log_2(\text{SNR})$

$$\begin{aligned}
 DL_4 = & \frac{T - \tau_1}{T} [P(H_1)P(H_0)(1 - p_d^1)C_{010x} + P(H_1)^2(p_d^1)C_{111x}] \\
 & + \frac{T - \tau_1 - \tau_2}{T} + \left[\begin{aligned} & P(H_1)^2(1 - p_d^1)(1 - p_d^2)C_{1100} \\ & + P(H_1)P(H_0)p_d^1(1 - p_d^2)C_{0110} \end{aligned} \right] \quad (13)
 \end{aligned}$$

5 Simulation Results

In this section, numerically simulated results are presented to validate the proposed scheme over other conventional schemes. These conventional schemes are: (i) Conventional spectrum access with single sensing slot (Conv_I) [3] (ii) Conventional spectrum access with two sensing slots (Conv_II) [5], and (3) Hybrid spectrum access with single sensing slot (Hybrid_I) [6]. The simulation environment considers one PU and multiple SUs placed randomly within the communication range of PU. The parameters used in simulation are given in Table 6. The values of the simulation parameters are same as considered in [3, 5, 6] and the values of P_d and P_f are considered as per IEEE 802.22 standard [21].

Figure 9 shows comparison of the secondary throughput for proposed hybrid spectrum access scheme with other three conventional schemes. It has been observed that the secondary throughput achieved Conv-I scheme is less as compared to the

Table 6 Simulation parameters [3, 5, 6, 21]

S. No.	Parameter	Value
1	T	100 ms
2	$P(H_0)$	0.1
3	$P(H_1)$	0.9
4	$P_f = p_f^1 = p_f^2$	0.1
5	$P_d = p_d^1 = p_d^2$	0.9
6	P_p	4 W
7	P_1	6 W
8	P_2	0.5 W
9	T	5 ms
10	N_p	0.04 W
11	f_s	6 MHz

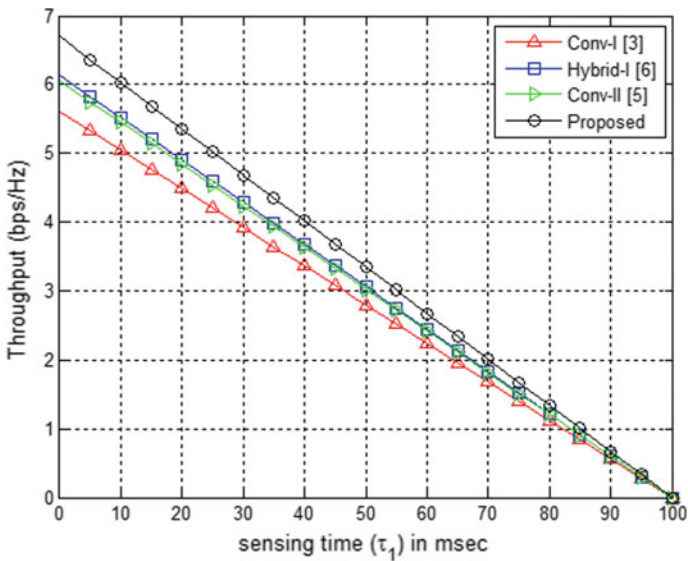


Fig. 9 SU Throughput comparison with respect to sensing time

other three schemes. This is due to the reason that conventional method allows SU to transmit in a channel on detecting PU absent from it. To overcome this bottleneck, Hybrid-I scheme allows SU to transmit in underlay and interweave mode based on the presence and absence of PU from channel, respectively. The scheme improves secondary throughput significantly however, similar to [3], no attempt has been made to correct the sensing error. To overcome uncertainties in sensing results, Conv-II scheme uses two sensing slots. Since, data transmission is allowed on detecting channel idle only and both sensing slots are of equal duration, the total transmission

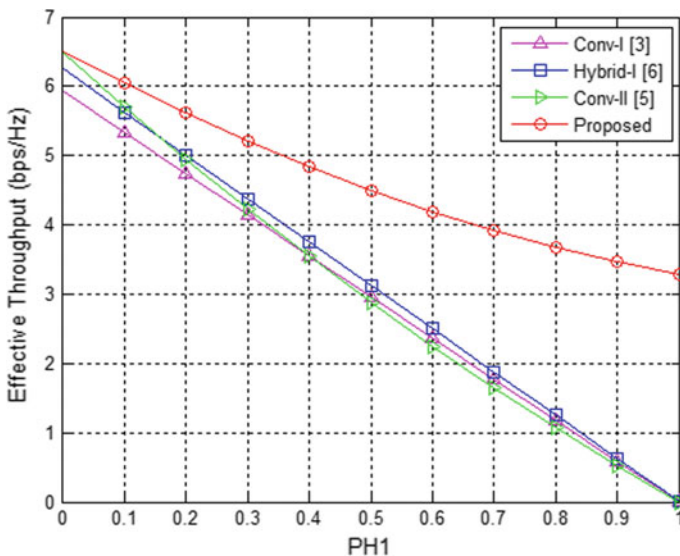


Fig. 10 Comparison of effective SU throughput with respect to PH1

time reduces significantly. However, the scheme performs equally well as Hybrid-I scheme and effective throughput of both the schemes is same. It has also been observed that proposed hybrid spectrum access scheme has a potential to improve effective SU throughput significantly by exploiting transmission opportunities more accurately with the help of two sensing slots.

The comparison of effective secondary throughput with respect to the probability of channel occupancy by primary user is shown in Fig. 10. It has been observed that for the parameters given in Table 5, the effective throughput of the proposed scheme is significantly high as compare to the other conventional schemes. For example when primary user is absent from a channel, the performance of the proposed scheme and Conv-II scheme is same and effective throughput is 5% and 8% more as compare to the Hybrid-I and Conv-I scheme, respectively. When channel is partially occupied by primary user, the proposed scheme improves SU throughput by 23% as compare to the other conventional schemes. It can also be observed that when channel is fully occupied by PU, proposed scheme has potential to achieve 50% more throughput as compare to the schemes proposed in [3, 5, 6].

In dynamic spectrum sharing scenario, when SU is not able to sense PU in a channel and transmits in interweave mode, the whole transmission results into data loss. Figure 11 shows the comparison of data loss with respect to PH1 for the proposed scheme with conventional schemes studied in this paper. It has been observed that for Conv-I and Hybrid-I scheme, data loss increases significantly with the probability of PU being active in channel increases. However, for Conv-II scheme and proposed scheme data loss is equal and decreases with the probability of PU being in a channel increases. For example, when PU is present in a channel, data loss of Conv-II and

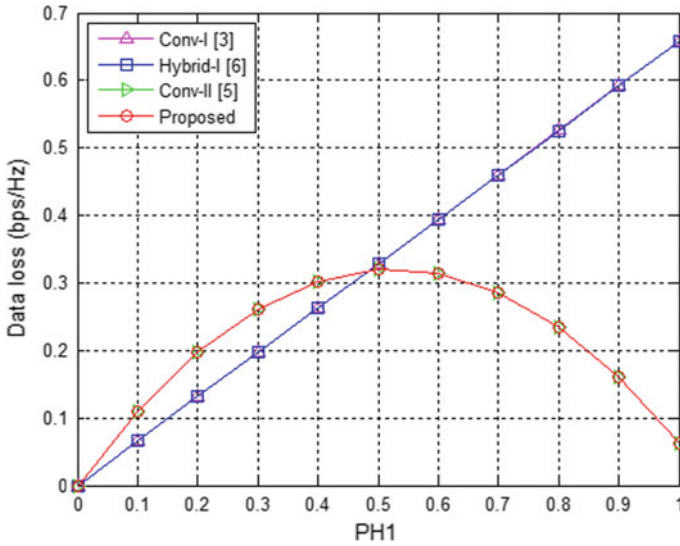


Fig. 11 Data loss comparison as a function of PH1

proposed scheme is 89% less than Conv-I and Hybrid-I scheme. Comparing Figs. 9 and 10, it is clear that proposed scheme has a potential to increase SU throughput significantly without increasing data loss as compared to Conv-II scheme discussed in this paper.

6 Conclusion and Future Scope

In this paper, hybrid spectrum access scheme is proposed for the efficient utilization of frequency spectrum. The scheme utilizes two sensing slots for the accurate detection of PU in a channel to improve SU throughput and to reduce the data loss. The analytical expression for the achievable secondary throughput and data loss have been derived and compared with other existing schemes with one and two sensing slots. Based on the results, it is concluded that the proposed scheme has a potential to increase SU throughput by 50% with zero data loss in comparison with other conventional schemes when PU is present in a channel. In future, the work may be extended further to evaluate the impact of adding second sensing slot in modified frame structure on the energy efficiency of the secondary communication system.

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