Advanced Frame Structures for Hybrid Spectrum Access Strategy in Cognitive Radio Communication Systems

Prabhat Thakur, Alok Kumar, S. Pandit, G. Singh, and S. N. Satashia

***Abstract*— In this letter, we have exploited a novel hybrid-cum-improved spectrum access technique for significant improvement in the throughput and data-loss rate. This proposed technique comprises of hybrid spectrum access and improved frame structure strategies of the cognitive radio communication system. Also, the closed-form expressions for throughput and data-loss of these approaches are derived. Moreover, the proposed approaches are validated numerically as well as with reported literature.**

***Index Terms*— Cognitive radio, interweave, hybrid, spectrum access, throughput, underlay.**

I. INTRODUCTION

THE HYBRID spectrum access (HSA) is an advance technique which exploits the interweave and underlay spectrum access strategies, simultaneously to enhance the spectral efficiency [1], [2] and throughput [3]. In HSA, the cognitive user (CU) senses its environment and transmits the data with full and constrained power on the idle and active sensed channels, respectively. As the spectrum sensing is a very prominent phenomenon, therefore its performance should be significantly high. The performance metrics of spectrum sensing technique are the probability of detection (P_d) and probability of false alarm (P_f) [4] and these values must be high and low, respectively. The sensing time needs to be high to satisfy this criterion, which imposes the lower-bound on the value of sensing time [5]. The sensing and data transmission time are inversely proportional to each other [6], which decreases the achievable throughput of the hybrid cognitive radio communication system (CRCS). Therefore, to improve the throughput, we need to modify the relation between sensing and data transmission time. Various researchers have modified this relation for the conventional (interweave approach) CRCS by introducing improved frame structures [4], [6]. The throughput maximization for CU is the prime objective of the CRCS, therefore, numerous researchers have exploited the HSA and frame structures individually for throughput maximization [1]–[4], [6], [7]. However, to the best-of-the author's knowledge, the improved frame structures are not incorporated in the HSA techniques to analyze the joint effects on the throughput of CU and data loss. Therefore, we have presented a novel hybrid-cum-improved spectrum access (HISA) technique for significant improvement in the throughput, data-loss rate and interference at the PU.

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P. Thakur, A. Kumar, S. Pandit, and G. Singh are with the Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Waknaghat 173215, India, (e-mail: prabhat.thakur@mail.juit.ac.in; alok.kumar@juit.ac.in; shweta.pandit@juit.ac.in; ghanshyam.singh@juit.ac.in).

S. N. Satashia is with the Space Application Centre, Indian Space Research Organization, Ahmedabad 380015, India.

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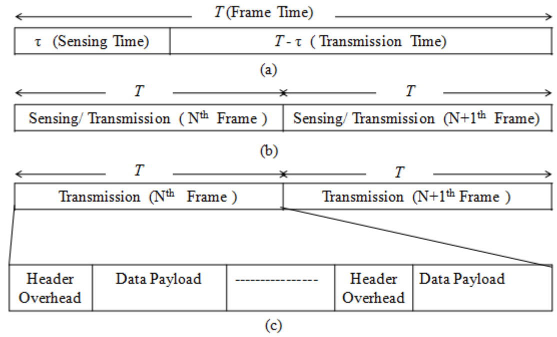

Fig. 1. The frame structure for CRCS (a) conventional, (b) advanced, and (c) improved.

II. RELATED WORK

A. Frame Structures

The conventional frame structure for CRCS consists of two phases i.e. the sensing phase and data transmission phase as shown in Fig. 1(a) [4]. Here, the CU senses the channel in time τ and rest of the time $(T - \tau)$ is used for data transmission. However, the major limitation of this frame structure is the sensing-throughput trade-off [7]. Therefore, to conquer this limitation, a novel architecture has been proposed in [6], in which the sensing and transmission are parallel phenomenon. The sensing information achieved through N^{th} frame is used for data transmission in $(N + 1)^{\text{th}}$ frame as shown in Fig. 1(b). However, the limitation of this approach is the outdated sensing information. As the sensing information of previous frame is used for transmission in the current frame, the CU will not regulate power due to unawareness of the PU state in the current frame. Therefore, the entire data of colliding frame on the emergence of PU gets lost, which results decrease in the throughput. To improve the throughput, a new architecture is proposed by Pandit and Singh [4], in which the frame is divided into two or more blocks and each block consists of two sub-blocks, namely, the header overhead and data payload as shown in Fig. 1(c), where the header overhead consists of flag-bit. The sensing is the continuous phenomenon in the entire time frame, however the results are taken out at the particular overhead block. The flag-bit uses the sensing result of same frame which is computed up to that time (starting time of the header overhead block) and the flag-bit is set if the sensing results are different from previous frame's sensing results. The frame structure presented in Fig. 1(c) overcomes the limitations of previous frame structure shown in Fig. 1(b) because the frame's sensing decision is used in the same frame to make spectrum access decision.

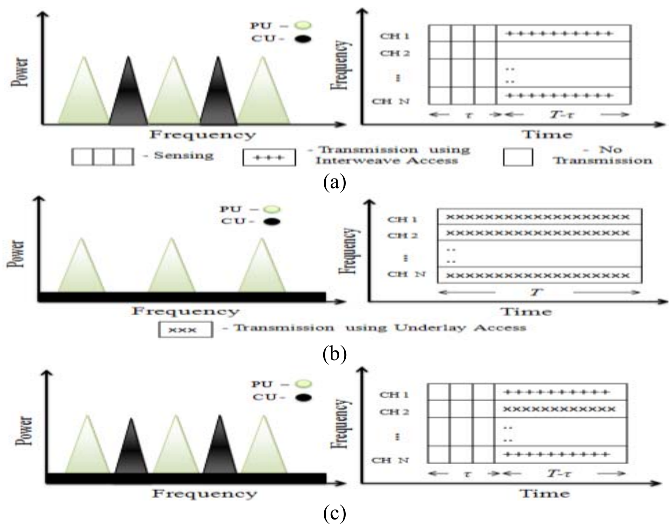

Fig. 2. The spectrum access strategies in cognitive radio communication systems (a) Interweave (b) Underlay and (c) Hybrid access.

B. Spectrum Accessing Strategies

The spectrum access is an integral part of CRCSs, hence various researchers/scientists have exploited the spectrum access techniques and classified as the interweave, underlay, and hybrid [3]. The interweave is a primary spectrum accessing strategy in which the CU senses its environment and sets up communication only on the idle sensed channels [7], [9], which means the spectrum sensing is prerequisite for this approach as shown in Fig. 2(a). However, in the underlay technique [3], [9], the sensing is not an essential phenomenon because the CU sets up communication in such a way to protect the PU from interference as shown in Fig. 2(b). The conventional strategies used to save the PU from the interference are the power control, beam forming and spread spectrum etc [8]. The interweave and underlay techniques are unable to exploit the spectrum intelligently because in the interweave approach, the CU needs to switch the communication on the emergence of PU however have to stop if all other channels are active. On the other hand, in the underlay technique, the seamless communication is possible, however the achievable data rate is a limiting factor due to low power transmission even in the absence of the PU [2]. Therefore, to overcome the limitations of both approaches, a hybrid approach which comprise of these two approaches have been proposed [1]–[3], and the spectrum sensing is the prerequisite as shown in Fig. 2(c). In this technique, the active and idle channels are accessed via underlay and interweave approach, respectively. The author's contribution in this letter is summarized as follows.

- Two novel frame structures are proposed in which idle sensed channels are accessed via interweave strategy, however the active sensed channels are using underlay strategy.
- The closed-form expressions for the throughput of CU and data loss in the proposed frame structures are derived.

III. Proposed Frame Structures for Hybrid Spectrum Access Technique

The data communication using time frames is in fashion and is also exploited prominently in the HSA technique. However,

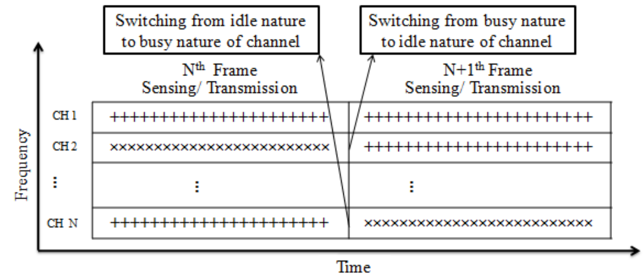

Fig. 3. 1st proposed frame structure for HISA technique.

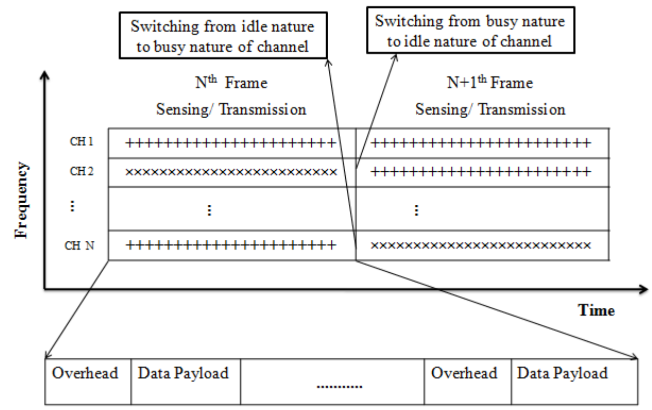

Fig. 4. 2nd proposed frame structure for HISA technique.

the frame structure for this technique is still in its infantry stage as shown in Fig. 2(a), where the entire time-frame is divided into two phases, namely, the sensing phase and data transmission phase and its limitation is similar to that of the conventional frame structure as shown in Fig. 1(a) i.e. the sensing-throughput trade-off. Therefore, in order to avoid this trade-off, we have proposed two novel frame structures for HSA technique as shown in Fig. 3 and Fig. 4. The proposed frame structures outperform over Fig. 1(b) and Fig. 1(c) as an idle and active sensed channels are accessed using the interweave and underlay access strategies, respectively. However, in Fig. 1(b) and Fig. 1(c), only the idle sensed channels are accessed for communication via the interweave strategy and the active sensed channels remain unutilized. In the 1st proposed frame structure as shown in Fig. 3, the spectrum sensing and data transmission are parallel phenomenon however, the sensing decision at previous frame is used for data transmission at current frame as similar to Fig. 1(b). As the sensing information confirms the switching of channels from idle to busy/active or vice-versa, the CU needs to switch the transmission from interweave to underlay or vice-versa, respectively. However, the limitation of this model is similar to that of the frame structure in Fig. 1(b) i.e. as the channel switch from idle to active state, the data of colliding frame gets lost. Therefore, in order to conquer this issue, one more frame structure for HSA technique is proposed as shown in Fig. 4, in which the frame is divided into two or more blocks and each block consists of two sub-blocks, namely, the overhead and data payload. The overhead block contains flag-bit and gets set if the sensing information (from the same frame up to the starting time of overhead block) decision is different from previous frame. Thus, the problem of data loss in the colliding frame for the HSA strategy is conquered.

TABLE I
THE DATA RATES OF CU FOR VARIOUS CONDITIONS

Sensing State	Original State	Data rate
idle	idle	$C_{00} = log_2\left(1+\frac{P_1\, h_{ss}}{N_p}\right)$
active	idle	$C_{10} = log_2\left(1+\frac{P_2\, h_{ss}}{N_p}\right)$
active	active	$C_{11} = log_2\left(1+\frac{P_2\, h_{ss}}{N_p + P_p\, h_{ps}}\right)$
idle	active	$C_{01} = log_2\left(1+\frac{P_1\, h_{ss}}{N_p + P_p h_{ps}}\right)$

IV. Analysis of Throughput and Data Loss

The throughput maximization for the conventional CRCS has been exploited in detail in [4] and [6]. For the spectrum sensing, the binary hypothesis for the received signal $r(t)$ is as follows. The H_0 and H_1 confirms the absence and presence of the PU, respectively.

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

where h, $w\,(t)$ and $s\,(t)$ denotes the channel gain, additive white Gaussian noise (AWGN) and the transmitted signal of the PU, respectively. For the simplicity of mathematical expressions, initially, we have derived the data rates for the four possible cases of the transmission as shown in Table I. In which h_{ss} and h_{ps} are the channel gains of the CU-pair and PU transmitter to the CU receiver, respectively. N_p and P_p denotes the noise power at CU receiver and PU transmitted power, respectively. The P_d defines under the hypothesis H_1, the probability of correct detection of the PU whereas, P_f defines under the hypothesis H_0, the probability of false alarm of the presence of PU [5]. For the better protection of the PU, the value of P_d must be high however, the CU can access the available band efficiently if the value of P_f is low. The expression for throughput of the conventional single channel cognitive radio is as [6]:

$$TP = \frac{T-\tau}{T}\left[P(H_0)(1-P_f)C_{00} + P(H_1)(1-P_d)C_{01}\right], \tag{1}$$

where $P\,(H_0)$ and $P\,(H_1)$ are the probabilities of channel being idle and active, respectively. The throughput as given by (1) is with respect to the conventional frame structure for the single channel CRCS as shown in Fig. 1(a). Now we need to compute the throughput for HSA technique on bases of the concept as discussed in section III. We assume that if the PU is accessing the channel with interweave approach, it transmits power P_1 otherwise with underlay approach it transmits power P_2. The expression for throughput of the n[th] channel in Fig. 2(c) is:

$$TP_c = \frac{T-\tau}{T}\left[P\,(H_0)\left(1-P_f\right)C_{00} + P\,(H_1)\,(1-P_d)\,C_{01} + P\,(H_0)\left(P_f\right)C_{10} + P\,(H_1)\,(P_d)\,C_{11}\right], \tag{2}$$

Now the throughput of the 1[st] proposed scheme i.e. TP_1 (as shown in (3)), which is similar to that of (2) except the multiplying factor $(T-\tau)/T$, because the sensing and transmission are parallel phenomenon due to which zero-time is spend on the sensing only, and the entire time frame T is used for the data transmission. However, in the 2[nd] proposed scheme, definite time is used for the control-overhead where it needs to stop data transmission. Therefore, to compute the achievable throughput, we have considered this overhead time and throughput in this is TP_o as given in (4), where x and k are the overhead time and number of overheads per frame, respectively in Fig. 4. The achievable throughput of the 2[nd] proposed approach (TP_2) is the difference between the throughput of 1[st] proposed approach TP_1 and throughput in control-overhead time TP_o.

TABLE II
THE NUMERICAL VALUES OF THE SIMULATION METRICS

Metric	Value	Metric	Value	Metric	Value
T	100 ms	P_p	4W	fs	6 MHz
$P(H_1)$	0.1	h_{ss}	0.8	N_p	0.04 W
$P(H_0)$	0.9	h_{ps}	0.1	P_2	0.5 W
P_f	0.1	P_1	6 W	x	$5ms$
k	4	τ	5 ms		

$$TP_1 = \left[P\,(H_0)\left(1-P_f\right)C_{00} + P\,(H_1)\,(1-P_d)\,C_{01} + P\,(H_0)\left(P_f\right)C_{10} + P\,(H_1)\,(P_d)\,C_{11}\right], \tag{3}$$

$$TP_o = \frac{x \times k}{T}\left[P\,(H_0)\left(1-P_f\right)C_{00} + P\,(H_1)\,(1-P_d)\,C_{01} + P\,(H_0)\left(P_f\right)C_{10} + P\,(H_1)\,(P_d)\,C_{11}\right], \tag{4}$$

$$TP_2 = TP_1 - TP_o, \tag{5}$$

The data loss occurs in the system when the data are transmitted with full-power P_1 (interweave transmission) and the PU resumes its transmission during data transmission period which means there is no data loss in the underlay transmission. As the hybrid transmission consists of interweave and underlay transmission, therefore the data loss of interweave and hybrid approach will be same. The data loss of conventional (interweave) approach is total transmitted data during the data transmission phase and is:

$$DL_c = \frac{T-\tau}{T}\left[P(H_0)(1-P_f)C_{00} + P(H_1)(1-P_d)C_{01}\right], \tag{6}$$

The 1[st] proposed frame structure transmits on the entire time frame, therefore the data loss is:

$$DL_1 = \left[P\,(H_0)\left(1-P_f\right)C_{00} + P\,(H_1)\,(1-P_d)\,C_{01}\right], \tag{7}$$

The data loss in the 1[st] proposed approach is very high, however in the 2[nd] proposed model, only particular data payload block will be lost and the data loss is:

$$DL_2 = \left[\frac{1}{k}\left\{P\,(H_1)\,(1-P_d)\,C_{01} + P\,(H_0)\left(1-P_f\right)C_{00}\right\}\right] - \left[\frac{x}{T}\{P(H_0)(1-P_f)C_{00} + P(H_1)(1-P_d)C_{01}\}\right], \tag{8}$$

V. Simulation and Results

In this section, we have presented the numerically simulated results of the proposed approaches and have compared with that of the conventional approaches. The values of metrics considered in the simulation are shown in the Table II.

The value of P_d for the given values of τ, P_f, fs and γ is computed using (5) as in [4]. The variation

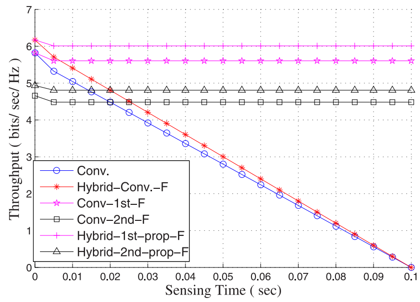

Fig. 5. The throughput for conventional and proposed approaches.

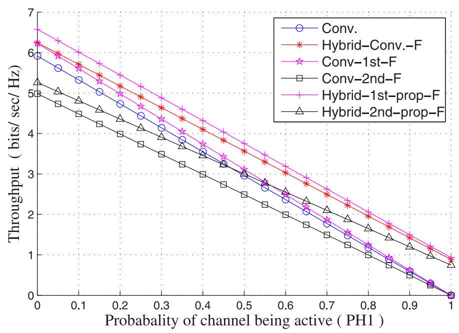

Fig. 6. The throughput versus $P(H_1)$ for various approaches.

of throughput of CU with sensing time for various spectrum access techniques as follows: 1) Conventional, 2) Hybrid spectrum access with conventional frame structure (Hybrid-Conv-F), 3) Conventional spectrum access with 1st advanced frame structure (Conv-1st-F), 4) Conventional spectrum access with 2nd improved frame structure (Conv-2nd-F), 5) Hybrid spectrum access with 1st proposed frame structure (Hybrid-1st-prop-F), and 6) Hybrid spectrum access with 2nd proposed frame structure (Hybrid-2nd-prop-F), are presented in Fig. 5. It is depicted that the throughput in approaches with advanced frame structures are not declining like that of the conventional approaches. The proposed hybrid approaches with 1st and 2nd frame structures i.e. the Hybrid-1st-prop-F and Hybrid-2nd-prop-F provide enhanced throughput as compared to that of the conventional approaches with the same frame structures, due to efficient utilization of active channels through the underlay transmission.

The relation between throughput of the CU and the probability of channel being active ($P(H_1)$) is presented in Fig. 6. It is clear that the Hybrid-1st-prop-F provides the highest throughput which is inversely proportional to the $P(H_1)$. The throughput of the Conv-2nd-F is lowest among all the cases, however in the proposed Hybrid-2nd-prop-F the throughput is low only till the $P(H_1)$ is 0.5 and above 0.5, it becomes the 3rd highest throughput among all considered scenarios. Moreover, the throughput becomes zero in the conventional approaches, however in the hybrid approaches it never becomes zero due to underlay transmission in the presence of PU. To analyze the data loss of the proposed and conventional approaches, the variation of data loss with the ($P(H_1)$) is presented in Fig. 7. The data loss in the Hybrid-1st-prop-F and Conv-1st-F is highest, as entire time frame gets lost on the emergence of PU. However, in the Hybrid-2nd-prop-F and Conv-2nd-F approaches, the data loss is comparatively very low because only the data of the particular data payload block gets lost. Moreover, the data loss only occurs if the data is transmitted

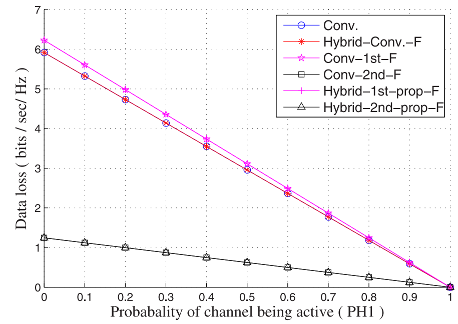

Fig. 7. The data loss of the CU versus $P(H_1)$ for various approaches.

with full-power (P_1) i.e. interweave transmission and PU appears during the transmission, therefore the data loss of the interweave and hybrid transmission remains same and obtained results also support this statement. In addition, the data loss shows inverse relation with $P(H_1)$ and it is because of the interweave approach in which the transmitted data decreases with increase in $P(H_1)$. Further, as in the Hybrid-2nd-prop-F, the CU switches its interweave transmission to the underlay transmission on the emergence of PU, therefore the interference at the PU is also reduced significantly.

VI. Conclusion and Future Scope

We have proposed two frame structures for the HSA strategy in the CRCS and this concept is named as HISA. In addition to this, the throughput and data loss expressions for the hybrid spectrum assess strategy with conventional and proposed frame structures are also illustrated. The proposed approaches are better in terms of throughput as compared to that of the conventional approaches, however the selection of particular approach relies on the requirements and applications of the cognitive network such as for the throughput maximization, the 1st approach is better and for the reduced data loss and reliable PU communication, the 2nd approach outperforms. The throughput and data loss optimization by constraining various metrics is an exigent task and will be reported in the future communication.

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