Informed Spectrum Discovery in Cognitive Radio Networks using Proactive Out-of-Band Sensing

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Abstract

Cognitive radio (CR) users, known as secondary users (SUs), should avoid interference with primary users (PUs) who own the licensed band, while trying to access it; when the licensed band is unused by the PUs. To detect PUs, spectrum sensing should be performed over in-band channels that are currently in use by SUs. If PUs return to access the band, SUs need to vacate it, disrupting the SUs' communication unless a non-utilized band is discovered. Obtaining a non-utilized band in a short period facilitate seamless communication for SUs and avoid interference on PUs by vacating from the channel immediately. Searching for a non-utilized band can be done through proactive out-of-band (OB) sensing. In this paper, we suggest a proactive OB sensing scheme that minimizes the time required to discover a non-utilized spectrum in order to continue communication. Although, the duration spent on OB sensing reduces the throughput of the CR networks that can be achieved on band being utilized, the lost throughput can be compensated in the new discovered band. We demonstrate that, the effect of our proposed scheme on the throughput owing to OB sensing is insignificant, while exhibiting a very short channel discovery time.

Keywords: Cognitive radio, spectrum sensing, proactive sensing, out-of-band sensing, throughput analysis

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1. Introduction

Owing to the prodigious interest in the use of ubiquitous communication, wireless technology has undergone a great revolution. For this reason, the spectrum bands/channels required(past) to support all types of wireless services had increased, as the technology has got more mature. Until now, the spectrum assignment was static to a specific licensed service and its users, causing spectrum scarcity because spectral resources are limited. In addition, a recent study has revealed that, spectrum scarcity occurs due to the inefficient spectrum allocation, rather than the actual physical shortage [1]. Another study, by the Federal Communication Commission (FCC) of the USA, has shown that 70% of the allocated spectrum is either unutilized or idle [2]. To mitigate this problem, the FCC proposed a new spectrum assignment policy, called dynamic spectrum access (DSA) by deploying cognitive radio networks (CRNs). Users of CRNs, known as secondary users (SUs), are required to identify the unutilized/idle licensed and unlicensed spectrum, unlike the so-called primary users (PUs), who have a statically assigned spectrum for their communications. The IEEE 802.22 group has defined a standard interface for physical (PHY) and medium access control (MAC) of a cognitive radio (CR) system [3].

Spectrum sensing is the key to enable CRNs. When SUs need to setup a CRN, the networks, through spectrum sensing, should first detect the presence of PUs or other SUs to avoid interference. Among several methods to detect PUs, energy detection is the most widely adopted approach in literature, because of its simplicity. Once an idle spectrum is found, SUs are required to keep monitoring it, to detect the potential return of PUs. To perform this, IEEE 802.22 defines two quiet periods, fast sensing and fine sensing, which the SUs use to decide the idleness of a channel [3]. Fast sensing is executed on a frame by frame basis and each lasts for a few milliseconds, whereas fine sensing is only triggered, if the data collected during fast sensing indicates that, there is some probability that PUs are using the spectrum. Performing fine sensing takes longer time than fast sensing. The intention of both is to perform in-band (IB) sensing and detect the activities of PUs.

If a PU suddenly appears and this is observed by SUs, then they should vacate the channel to avoid interference with PUs. This interrupts the transmission of SUs, unless another idle channel is found within a very short time. In such a scenario, SUs may either search for a new idle channel or access a prearranged backup channel that was discovered while operating on an previous channels. The former is known as reactive sensing and takes a longer time because SUs have no information about their environment, whereas the latter is called proactive out-of-band (OB) sensing [4, 6]. In this paper, OB sensing, unless stated otherwise, refers to proactive OB sensing. Even though it is easily implementable with dual antennas, one for data transmission and another for discovering an idle OB channel, the hardware cost is high and might cause severe interference between the antennas, degrading the SUs' service quality [5]. Furthermore, as indicated in [24], it suffices to use a single antenna to sense and transmit successfully. Therefore, we consider proactive OB sensing with a single antenna. We have to sacrifice, however, transmission time to be able to prepare backup and candidate channels for SUs vacation whenever PUs appear on the channel.

Our contribution is twofold. We propose a framework and method for proactive OB sensing, that reduces idle channel detection time. Firstly, we establish an OB quiet/sensing period to sense OB channels, with a duration that is less than or equal to fast sensing. Unlike fast sensing that is performed on a frame-by-frame basis, OB sensing is only triggered on few frames periodically. For instance, on the 4th, 8th, 12th … frames could be selected for OB sensing. The interval can be adjusted according to the network's condition. However, whenever fine sensing is required, OB sensing is scheduled for the following interval because interference with PUs should be avoided. During the OB sensing duration, SUs monitor independently, whether there is any PU activity in the channels, then make decisions about the observation and report the decision to the secondary base station (SBS) the decisions of the SUs, gives a weight, classifies, and determines the status of the observed channel. Each channel is then classified into different categories based on its weight. Channels with high weights are classified as a backup and channels with low weights are classified as candidates. The weight, class, and status of a channel are used to prioritize in case of a tie between any two channels. SBSs organize this information and store it as a look-up table that is updated every time an OB channel is observed. When SUs are forced to vacate a channel, the SBS selects an appropriate one from the look-up table and informs SUs to switch to that channel. This saves the time required to discover a new idle channel, rather than randomly or sequentially searching for idle channels, as in reactive sensing. Secondly, even though proactive sensing is deemed to reduce throughput, we verify that with proper implementation the effect of OB sensing on throughput is insignificant. We do that, by mathematically deriving the achievable and the aggregate throughput of the system during cooperative sensing; a similar calculation was performed for an individual user in [8]. Approach of selfish SUs are avoided to keep off other game-theoretic issues. In addition, most studies only mention backup and candidate channels and avoid establishing which node is responsible for making the list or how to build and update the list. However, we also provide a clear view on which node will take responsibility for maintaining the backup and candidate list, as well as, how it can be constructed. This research has a broader view to proactive OB sensing along with building a lookup table.

The rest of this paper is organized as follows. In Section 2, we introduce our system model and then in Section 3 related works are presented. Section 4, illustrates the informed channel discovery scheme in details. In Section 5, mathematical analysis of the throughput is derived and in Section 6, performance evaluation and numerical results are shown. Finally, in Section 7, we conclude this work.

2. System Model

In our system model, there are N secondary stations including a SBS. There are M channels that can be used by SUs and each can take one of two possible states, idle or busy. The list of notations is summarized in **Table 1**. Each user senses a channel using energy detection and sends its decision to the SBS. The available channels are categorized into four classes. Two main classes are described below whereas the remaining two are discussed in Section 4.

Backup channels: A set of channels where SUs first attempt to get to, when PUs appear on the channel being used. Once a certain channel is included as a backup channel set, it is regularly sensed using OB sensing. We assume that, the interval of OB sensing over one backup channel is fixed but longer than that of IB sensing.

Candidate channels: The channels other than the current one, backup, and occupied/unavailable channels, belong to the candidate channel set. Once a backup channel becomes unavailable, due to the appearance of a PU or because a certain candidate channel is better than any backup channel, that candidate will replace one of the backup channels that has low priority compared to the rest. We assume that, the interval of OB sensing over a candidate channel is fixed, but it is significantly longer than that, over a backup channel.

Table 1. List of notations and their descriptions.

Notations	Description	Not.	Description
I_{OB}^{ss}	Interval between two OB sensing events	R	Achievable rate
α	Min. interval between consecutive OB sensing	P_f	Probability of false alarm
β	Max. interval between consecutive OB sensing	P_d	Probability of detection
ω	OB or Fine IB sensing duration	W_j	Weight of channel j
T_{req}^{cs}	Time required for channel switching	T	Total duration of a frame
T_{req}^{nc}	Time required for discovering a new channel		
SE_{ij}	OB sensing by user i on channel j	τ	Fast IB sensing duration
$C_{sen}^{tot\_j}$	# of counts of total OB sensing on channel j	T_{req}^{ss}	Time required for spectrum sensing
C_{idle}^{j}	# of counts of channel j to be found idle		
C_0	Channel capacity without PU presence	T_{req}^{dx}	Time required for data exchange
CS_j	Channel status of channel j		
r	Min # of channels visited before idle channel is found	T_{idle}^{cur}	Idle time of SUs current operating channel
C_1	Channel capacity with presence of PU		

We consider two types of frames to be used in this system. One type only incorporates the duration τ of IB channel sensing to perform fast sensing, whereas the other type incorporates both the duration τ and the OB sensing duration ω that could be used for fine sensing [6]. In both cases, the total frame duration is fixed at T; both τ and ω are given in milliseconds. **Fig. 1** shows the frame structure. As we have described earlier, whereas IB sensing is performed for every frame, OB and fine sensing are performed with a longer period or only when necessary. Fine sensing and OB sensing cannot be performed in the same frame. Instead, OB sensing is postponed to the next frame and fine sensing is performed first, because IB sensing should be performed prior to OB sensing.

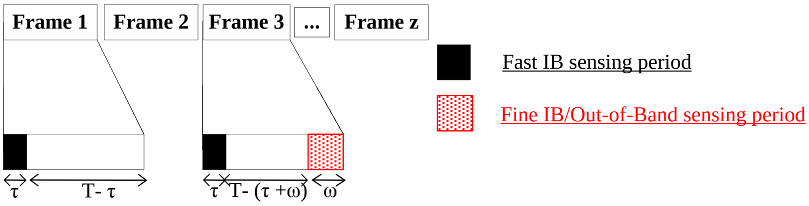

Fig. 1. Design of in-band and out-of-band frames.

Energy Detection: in this system we assume SUs are equipped with energy detector for spectrum sensing. The energy detector, starts by sampling signals from the spectrum and proceeds hypothesizing over the sampled signals. Then it determines the presence or absence of PUs using the following equations obtained from [8]. However, due to the cooperative behavior of SUs in our work, these equations are modified in section 5.1 to suit our purpose.

The presence and absence of PUs measured at SUs can be represented by two hypotheses H_1 and H_0, respectively:

$$y(n)=\begin{cases} s(n)+u(n) & H_1, \\ u(n) & H_0. \end{cases} \tag{1}$$

Here, $y(n)$ is the received signal at SUs, $s(n)$ is the signal transmitted by PUs and $u(n)$ is Gaussian noise. The test statistic is given as follows:

$$T(y)=\frac{1}{N}\sum_{n=1}^{N}\left|y(n)\right|. \tag{2}$$

Under a complex valued phase-shift keying (PSK) signal and circularly symmetric complex Gaussian (CSCG) noise, based on the test statistics, the probabilities of detection P_d and false alarm P_f for a certain threshold ε are, respectively, given by:

$$P_d(\varepsilon,\tau)=Q\left(\left(\left(\frac{\varepsilon}{\sigma_u^2}\right)-\gamma-1\right)\sqrt{\frac{\tau f_s}{2\gamma+1}}\right). \tag{3}$$

$$P_f(\varepsilon,\tau)=Q\left(\left(\left(\frac{\varepsilon}{\sigma_u^2}\right)-1\right)\sqrt{\tau f_s}\right). \tag{4}$$

where γ is the SNR of the channel of interest and $Q(.)$ the complementary distribution function of the standard Gaussian, i.e.,

$$Q(.)=\frac{1}{\sqrt{2\pi}}\int_x^{\infty}\exp\left(-\frac{t^2}{2}\right)dt. \tag{5}$$

Each user is equipped with an energy detector that can detect PUs with a high probability of detection $P_d=0.9$ and can only falsely declare absence of a PU with a false alarm probability $P_f=0.1$. Therefore, interference on PUs is very low and SUs can utilize the spectrum confidently, once found to be free. Detailed derivation and explanation of equations (1–5) can be found in [8].

3. Related Works

Previous work has shown the importance of proactive sensing. The notion of backup and candidate channels has been introduced [10], to aid the discovery of an opportunity, but less attention has been given to developing a mechanism for building such a list. Chang et al. [11] propose that, SUs probe a channel and transmit based on optimally derived information. However, the channel is exploited or sensed by only one user and severe interference could be caused if any other user makes the wrong decision. Zao et al. [12] suggest a decentralized MAC, through which individual users have to choose a subset of channels and must determine if transmission is possible based on the outcome of sensing. Nevertheless, this approach does not use prioritization, but rather senses a subset. Kim and Shin, [13] approach the problem by sorting channels based on their probability of idleness. Even though the solution is dependent on OFDM systems, it maximizes the chance of finding an idle channel. Datla et al. [14] suggest that, whenever a channel is found to be occupied, SUs linearly reduce their preference on sensing that channel. Optimality of the delay encountered in discovering an opportunity, however, is not guaranteed.

Several models have been proposed by researchers to demonstrate the importance of proactive sensing. In [22], the authors suggest an approach for optimizing the time for IB sensing (monitoring) and OB sensing (searching). During monitoring, sensing is performed with a detection threshold of the current channel, so that a PU is protected and the sensing time is minimized. Sensing time, consumed energy, the false alarm probability of each channel, and the number of channels to be sensed, are calculated during searching. Having a specific analysis for an individual channel is not feasible and consumes more time. Besides, sensing in [23] makes the use of channel history stored in a database. The main idea of the work is to use history to minimize the number of channels to sense and then identify the presence or absence of PUs in those. Despite its merit, the approach does not consider the overhead due to information exchange, and also does not provide a clear description of the communication between the database and the users. In [18] and [19], the authors proposed a method for predicting future channel status based on the traffic pattern in channels of interest. The idea is to classify channels into deterministic and stochastic, according to the pattern in PUs' ON and OFF durations. But the authors do not show the time required to find a non-utilized channel; rather they only focus on minimizing the number of channel switches.

Some of these studies are based on single-user sensing that could lead to interference with a PU, whereas others require dual antennas for sensing and communication. State-of-the-art research, however, has shown that cooperative sensing could provide a better insight into the spectrum environment [17]. In addition to that, it is clearly shown that a single antenna can efficiently be used for sensing and transmission [24]. Another issue in sensing is the type of sensing techniques that SUs should use to detect the activity of PUs. In this study, we adopt energy detection as default because its simplicity and effectiveness have been well known in the literature. For this reason, in the following section, we give a brief explanation on the principles of energy detection from earlier work.

4. Informed Channel Discovery Scheme

4.1 Objective

When SUs are forced to vacate a channel, our main objective is to reduce the time required to obtain a new idle channel, T_{req}^{nc}, while not reducing much of the transmission time for OB sensing because, the data collected during OB sensing is used for channel discovery. T_{req}^{nc} is the sum of the time required for i) spectrum sensing T_{req}^{ss} ii) channel switching T_{req}^{cs} and iii) sensing data exchange T_{req}^{dx}. Assuming r channels will be visited before finding a new idle channel, reducing T_{req}^{nc} means visiting as small a number of channels as possible to discover a non-utilized channel while investing less time to gather information (i.e., minimize the number of channels to visit, r, while keeping I_{OB}^{ss} between α and β). Mathematically, our objective can be written as

$$\begin{gathered}\min_{r} \quad \frac{1}{P_d}\sum_{i=1}^{r}(T_{req}^{cs}+T_{req}^{ss}+T_{req}^{dx}) = T_{req}^{nc} \\ s.t. \quad \alpha \le I_{OB}^{ss} \le \beta.\end{gathered} \tag{6}$$

The intervals between consecutive OB sensing events, I_{OB}^{ss}, can be as short as α, to keep the freshness of the information and to sense more channels, and can be as long as β, to minimize the effect on the throughput. If it is shorter than α, the throughput will degrade, and if greater than β, the information will be irrelevant. The higher the probability of detection, the easier it is for SUs to discover a new channel, which in turn implies that a shorter time is required to discover a new channel. However, the probability of detection is always between 0 and 1 and has an inversely proportional effect on the time required for channel discovery, as shown in (6).

4.2 Observation

The first step in informed opportunity discovery is to observe OB channels during OB sensing intervals. At each OB sensing instance, the SBS selects a channel to observe and announces it to SUs**.** Until every OB channel is sensed twice, the channels are sequentially sensed. Sensing is performed twice because it is the least number required for computing the weight of a channel. An approach for calculating this weight will be discussed in the next section. After the two rounds, the channel selected as a backup is interleaved with other channels. For instance, assume that there are three channels, and that the first channel is selected as a backup channel after two rounds. The sequence can follow such an order: {1st-3rd-1st-2nd-1st…}. The channels amongst the backup channels can be selected sequentially or randomly. Then all involved SUs synchronously switch to the selected channel and carry out OB channel sensing. When the time allowed for observation has elapsed, each SU sends its decision to the SBS. Then, SUs switch back to the channel being used at that moment and preform fast sensing to ensure that the channel is still usable (i.e., there is no PU activity on it). The SBS then updates the look-up table. However, if fast sensing indicates there is certain PU activity on the channel, then SUs will be forced to perform fine sensing. **Fig. 2** shows the interleaving process of fast, fine and OB sensing.

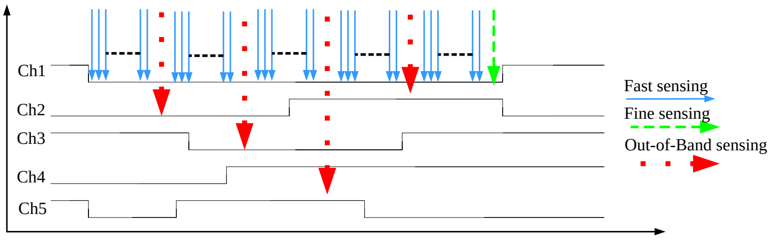

Fig. 2. Data collection about OB channels, while transmitting on the current channel; the solid arrow indicates IB sensing; the dotted arrow, OB sensing; and the dashed arrow, fine sensing.

4.3 Look-up table

As mentioned earlier, the look-up table is composed of elements such as status, weight, class, and priority. It is updated every time that OB sensing is carried out. Each of these elements is computed or decided separately. In this section, we will discuss the meaning and values of these elements, and explain how the look-up table is created at a SBS.

1. ***Status*** → this determines the presence and absence of PUs in the observed channel. Using energy detection, SU i carries out OB sensing on channel j, which is denoted by SE_{ij}; $1 < i < N, 1 < j < M$. SE_{ij}. The quantized decision is defined as follows:

$$SE_{ij} = \begin{cases} 0 & \textit{if channel is idle,} \\ 1 & \textit{if channel is busy.} \end{cases} \tag{7}$$

Each user sends its quantized result to the SBS (quantizing the decision has many benefits as discussed in [21]). The SBS receives the decisions and stores the results temporarily, for composing the look-up table. To decide the final status of a channel, the SBS uses a majority-rule fusion mechanism and equation (7). This rule has been chosen because it has performed better compared to the OR and AND rule [8, 17]. In the majority rule, a SBS declares the presence of PUs if more than half the users declare the presence of PUs; otherwise the channel is declared idle. Mathematically, the final status of channel j, $1 < j < M$, that has been sensed by N users is given as follows:

$$CS_j = \begin{cases} 0 & \textit{idle} \quad \textit{if} \quad \sum_{i=1}^{N} SE_{ij} \le \frac{1}{2} N, \\ 1 & \textit{busy} \quad \textit{if} \quad \sum_{i=1}^{N} SE_{ij} > \frac{1}{2} N. \end{cases} \tag{8}$$

2. ***Weight*** → a weight is the metric to measure the idleness of a channel. Let C_{sen}^{tot-j} be the count of total OB sensing instances on channel j and C_{idle}^{j} be the count of OB sensing instances that channel j is found to be idle. The weight of channel j, which is denoted by W_j, is the ratio of idle instances to the total number of OB sensing instances and is given by

$$W_j = C_{idle}^{j} / C_{sen}^{tot-j}. \tag{9}$$

The values of C_{sen}^{tot-j} and C_{idle}^{j} are also stored in the look-up table. The SBS updates these values following every OB sensing duration. When a channel is found to be idle, both C_{sen}^{tot-j} and C_{idle}^{j} are incremented by one; otherwise if the channel is busy only C_{sen}^{tot-j} is incremented. Because $C_{sen}^{tot-j} \ge C_{idle}^{j}$, the weight is between 0 and 1 (i.e., $0 \le W_j \le 1$).

3. ***Class*** → this element is used to categorize the channels into different classes. There are four classes, backup (B), candidate (C), not available (NA), and under-utilization (U). Channels are categorized based on the status of a channel, when it was last sensed, and its weight. A channel that is currently in use is classified as "*U*", channels with weight $W_j < \Delta$ are classified as "*NA*", channels with weight $W_j \geq \Delta$ that were last sensed as ***busy*** OB are considered as "*C*" and finally channels with weight $W_j \geq \Delta$ and ***idle*** OB sensing result are categorized as "*B*". The delta, Δ, can be varied according to the channel condition. In this work we set $\Delta = 0.5$ as the default.
4. ***Priority*** → this element of the look-up table is used to break ties between channels with the same weight, class, and status. For instance, if there are two backup channels with the same weight, class, and status, the channel which has been most recently sensed gets the highest priority. The priority of classes, from the lowest to the highest, follows the order $U < NA < C < B$. When PUs appear, the channel occupied will be added to the list of not available or candidates, based on its weight. The backup channel with the highest priority becomes the current channel.

The second stage of this scheme concerns updating the tables discussed earlier. For the sake of simplicity, we will explain through an example. Suppose, there are five channels in the networks; and, channel information has been accumulated. Table 2 shows the look-up table at a certain point in time. Because channel 4 and channel 5 are backup channels, which should be monitored frequently, SUs perform OB sensing on them twice within the allocated time. Assume that, during these OB sensing instances, channel 4, say, has been found to be ***idle*** on both occasions whereas channel 5 was found to be ***busy*** the first time and ***idle*** the second time. The look-up table is updated as in Table 3. The values in shaded boxes indicate the updates. According to the observation performed on OB channels it is now clear that channel 4 becomes more preferable than channel 5. Because channel 5 was busy for the first time, its priority decreased while channel 4's priority increased.

Table 2. Example of a look-up table.

	ch^1	ch^2	ch^3	ch^4	ch^5
Idle/C_{idle}^{j}	9	6	3	7	8
Total/C_{sen}^{tot-j}	10	10	10	10	10
Status	0	1	1	0	0
Weight	.90	.60	.30	.70	.80
Class	U	C	NA	B	B
Priority	4	3	-	2	1

Table 3. Updated look-up table later.

	ch^1	ch^2	ch^3	ch^4	ch^5
Idle/C_{idle}^{j}	9	6	3	9	9
Total/C_{sen}^{tot-j}	10	10	10	12	12
Status	0	1	1	0	0
Weight	.90	.60	.30	.75	.75
Class	U	C	NA	B	B
Priority	4	3	-	1	2

4.4 Opportunity Discovery

The final stage or the main goal of creating this look-up table is to easily discover a new idle channel when SUs are forced to leave the operational channel they are on. There is no complicated task, to be carried out at this stage. If the fine sensing confirms that there is PU activity on the channel, the SBS informs all SUs to switch to the channel with the highest priority. Then all SUs synchronously vacate the channel. If the highest priority channel is unavailable then the second highest is selected, and so on. If all priority channels are unavailable, the SBS starts to switch channels randomly. Furthermore, it clears all entries of the look-up table and starts again.

4.5 Comparison

In this section, we show the effectiveness of our scheme in comparison with random and sequential opportunity discovering techniques. Both random and sequential techniques use reactive sensing, whereas our scheme employs proactive sensing. **Fig. 3** demonstrates the ease with which SUs can find an idle channel using the proposed scheme.

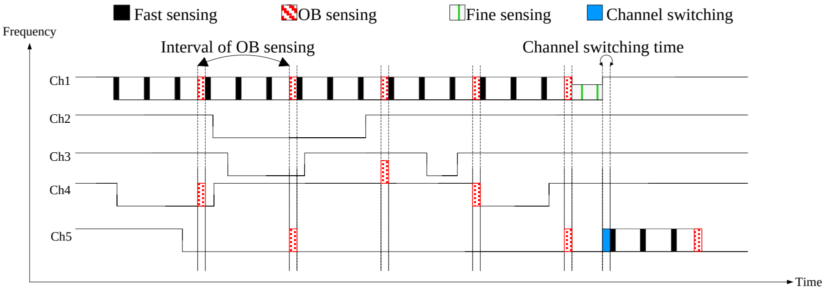

Fig. 3. Operation of the proposed sensing scheme.

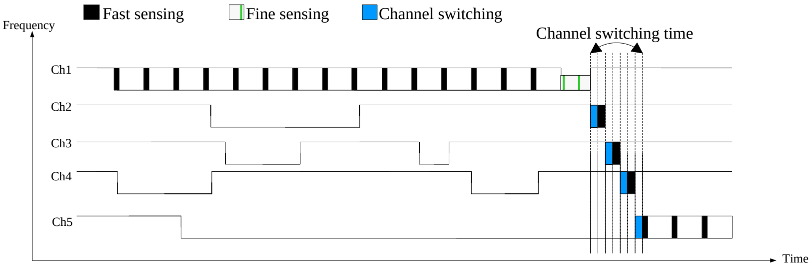

Fig. 4. Operation of the sequential sensing scheme.

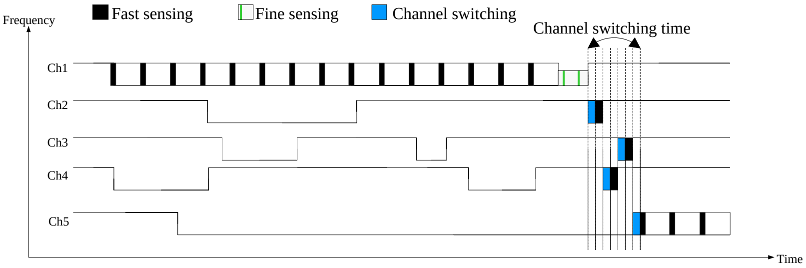

Fig. 5. Operation of the random sensing scheme.

Fig. 4 shows the sequential technique. According to this scheme, SUs starts looking for a non-utilized channel if the channel they are using becomes unavailable, because of the presence of PUs. This scheme is summarized as follows. Assuming channels are sequentially indexed, SUs go through the list of allowed channels starting from the first. Once they have gone through the list, they repeat the procedure until a vacant channel is found. This scheme could accidentally discover a channel in a less time than the proposed scheme; however, in the long run it does not guarantee a good time and it is also not consistent.

Another reactive form of discovering a channel is random search. The only difference between sequential and random search is that during the latter, SUs look for an idle channel by arbitrarily selecting channels from a given list. This scheme does not guarantee a short time in the long run and it is not consistent. **Fig. 5** shows the random scheme.

There are also other reactive and proactive opportunity discovery schemes in literature. In the analysis section, the informed scheme is compared with two of the reactive schemes discussed here with two other proactive schemes proposed in [22] and [23].

5. Achievable and Aggregate Throughput

In the previous sections, we have described how sensing should be performed in order to discover a non-utilized channel quickly. Here, we will discuss the achievable and aggregated throughput of the system in the IB channel when our OB sensing is incorporated, by comparing the cases with and without it. The throughput discussed here is the network throughput rather than the individual user one.

5.1 Preliminary

Because we aim at analyzing the throughput of the network, we need to compute the probability of detecting or generating a false alarm depending on the number of users that are cooperating and the detection mechanism. A good survey of spectrum and cooperative sensing can be found in [21] and [25], respectively. We first discuss how the probabilities of users cooperating are calculated, by modifying the analysis of Section 2.1 and then use them to formulate the network throughput. Because there are multiple SUs that can identify the presence of PUs, we define the above hypotheses in equation (1) for the i^{th} user and j^{th} channel for $1 < i < N, 1 < j < M$ as follows:

$$y_{ij}(n) = \begin{cases} s_{ij}(n) + u_{ij}(n) & H_1^{ij}, \\ u_{ij}(n) & H_0^{ij}. \end{cases} \tag{10}$$

Following the modified hypotheses, and using (3) and (4), the probabilities of detection and false alarm for the *i*th user are defined as P_d^{ij} and P_f^{ij}, respectively, and are given by

$$P_d^{ij}(\varepsilon,\tau) = Q\left(\left(\left(\frac{\varepsilon}{\sigma_{u,ij}^2}\right) - \gamma - 1\right)\sqrt{\frac{\tau f_s^{ij}}{2\gamma_{ij} + 1}}\right). \tag{11}$$

$$P_f^{ij}(\varepsilon,\tau) = Q\left(\left(\left(\frac{\varepsilon}{\sigma_{u,ij}^2}\right) - 1\right)\sqrt{\tau f_s^{ij}}\right). \tag{12}$$

Furthermore, using equations (11) and (12), assuming all probabilities of detections are equal, $P_d^{ij} = P_d^i$ and all probabilities of false alarm are equal, $P_f^{ij} = P_f^i$, the new probabilities under the majority rule, which follows a binomial function, can be given by

$$\overline{P_d} = \sum_{k=0}^{N-\lceil N/2 \rceil} \binom{N}{\lceil N/2 \rceil + k} \left(P_d^i(\varepsilon,\tau)\right)^{\lceil N/2 \rceil + k} \left(1 - P_d^i(\varepsilon,\tau)\right)^{N-\lceil N/2 \rceil - k}. \tag{13}$$

$$\overline{P_f} = \sum_{k=0}^{N-\lceil N/2 \rceil} \binom{N}{\lceil N/2 \rceil + k} \left(P_f^i(\varepsilon,\tau)\right)^{\lceil N/2 \rceil + k} \left(1 - P_f^i(\varepsilon,\tau)\right)^{N-\lceil N/2 \rceil - k}. \tag{14}$$

5.2 Throughput

SUs achieve various possible throughputs depending on the channel capacity and the type of frames used for transmission (i.e., if the portion of the frame is used for OB sensing or not). In addition, the probability of the hypothesis, detection, and false alarm also contributes to the network throughput. The channel capacity when SUs operate on the PUs' spectrum, in the presence and absence of PUs, is denoted by C_1 and C_0, respectively. There are four scenarios in which SUs can operate in the spectrum, and the achievable throughput per frame under each scenario is summarized below.

1. When there is no PU and OB sensing is not used: $\left((T-\tau)/T\right) * C_0$
2. When there is no PU and OB sensing is used: $\left((T-\tau-\omega)/T\right) * C_0$
3. When there is PU but not detected, and OB sensing is not used: $\left((T-\tau)/T\right) * C_1$
4. When there is PU but not detected, and OB sensing is used: $\left((T-\tau-\omega)/T\right) * C_1$

For a certain spectrum band, suppose the probability that a PU is active is $P(H_1)$, and inactive $P(H_0)$, such that $P(H_1) + P(H_0) = 1$. Then the probability for the first and second scenarios to occur is given by $(1-\overline{P_f})P(H_0)$, and the probability for the third and fourth scenarios to occur is given by $(1-\overline{P_d})P(H_1)$. From the results in [8], and the new probability of detection and false alarm, we can define the actual throughput, or rate, achieved by the above four scenarios as follows:

$$R_{0,1} = \left((T-\tau)/T\right) * C_0 * (1-\overline{P_f})P(H_0). \tag{15}$$

$$R_{0,2} = \left((T-\tau-\omega)/T\right) * C_0 * (1-\overline{P_f})P(H_0). \tag{16}$$

$$R_{1,3} = \left((T-\tau)/T\right) * C_1 * (1-\overline{P_d})P(H_1). \tag{17}$$

$$R_{1,4} = \left((T-\tau-\omega)/T\right) * C_1 * (1-\overline{P_d})P(H_1). \tag{18}$$

From equations (15), (16), (17), and (18), the achievable throughput per frame of SUs, when using IB frames only, R_{IB}, and together with OB frame, R_{OB}, is given by:

$$R_{IB} = R_{0,1} + R_{1,3}, \tag{19}$$

$$R_{OB} = R_{0,2} + R_{1,4}. \tag{20}$$

Because we have a value for achievable throughput per frame, using a single IB or OB frame, from (19) and (20), the raw aggregated throughput can be calculated by adding the number of IB and OB frames sent over a certain idle channel. To do this we need to estimate the amount of time SUs spend on a certain channel before vacating it (i.e., the idle time of currently under-utilized channel T_{idle}^{cur} that can be estimated based on the computation in [7]). Using that fact, the total number of frames on T_{idle}^{cur}, given by F_{idle}^{tot}, can be obtained by dividing the ***idle*** time of the current channel by the frame duration: $F_{idle}^{tot} = T_{idle}^{cur} / T$. If, then, an OB frame is used during communication, the aggregate rate of the network R_{agg} is given by:

$$R_{agg} = R_{IB} F^{IB} + R_{OB} F^{OB}. \tag{21}$$

where F^{OB} is the number of OB frames used while the SUs are transmitting on the channel. $F^{IB} = F_{idle}^{tot} - F^{OB}$ is the number of IB frames, used during transmission on the current channel. However, if there is no OB sensing, all frames used will be IB frames only (i.e., $F^{IB} = F_{idle}^{tot}$), and there will be time used for reactive sensing. Therefore, the aggregate throughput of the system in equation (21) is calculated as follows:

$$R_{agg} = R_{IB} F_{idle}^{tot}. \tag{22}$$

6. Performance Evaluation and Numerical Results

In order to validate the performance of the informed scheme, we present numerical results using Matlab, with the following assumptions. To ensure that this work is compatible with the IEEE 802.22 standard and earlier studies, some of the simulation parameters have been taken from related works. The channel capacity with and without the presence of PUs on the channel is, respectively, given by $C_1 = 6.6137$ and $C_0 = 6.6582$. Other simulation parameters are given in **Table 4**.

Table 4. Simulation parameters and values.

Parameters	Value	Parameters	Value
SNR	20 dB	T_{req}^{dx}	2 s
number of channels	20	T_{req}^{cs}	20 μsec [15]
frame duration	100 ms	$P(H_0)$	0.8 [8]
$\tau = T_{req}^{ss}$	1 ms [3]	$P(H_1)$	0.2 [8]

We have randomly generated an ***idle*** and ***busy*** combination for 20 channels. SUs sense the channels using the Informed, Effective [22], Priority [23], Sequential, and Random sensing for a combination of busy and idle channels. For each scheme, SUs store the time required to discover an idle channel after vacation. We compare the performance of the proposed and other schemes, by computing the mean discovery time for 100 iterations of different idle/busy combination and using the given equations. OB sensing duration, ω, is taken to be 1 ms. **Fig. 6** shows the time required to discover a new channel using reactive and proactive sensing schemes. In this experiment, 10 SUs are cooperating. It is clear that the proposed and the other proactive sensing schemes greatly reduce the time required to discover a new channel. The discovery time of our informed scheme, T_{req}^{nc} = 2.03273 s, is slightly higher than the sum of T_{req}^{dx}, T_{req}^{ss}, and T_{req}^{cs} (2.02001 s), which is the time taken to discover one idle channel. This implies that, r, the number of visited channels before finding a new channel in the minimization problem is $r \le 2$, as $T_{req}^{nc} > 2.02001$. In general, the proactive discovery is much better than reactive category in all cases. However, the proposed scheme can still outperform both schemes compared, in discovering a new idle channel, as shown in the magnified section of **Fig. 6**. Numerically, the T_{req}^{nc} for *Effective* [22] and *Priority* [23], respectively, require 10 ms and 32 ms more compared to *Informed*.

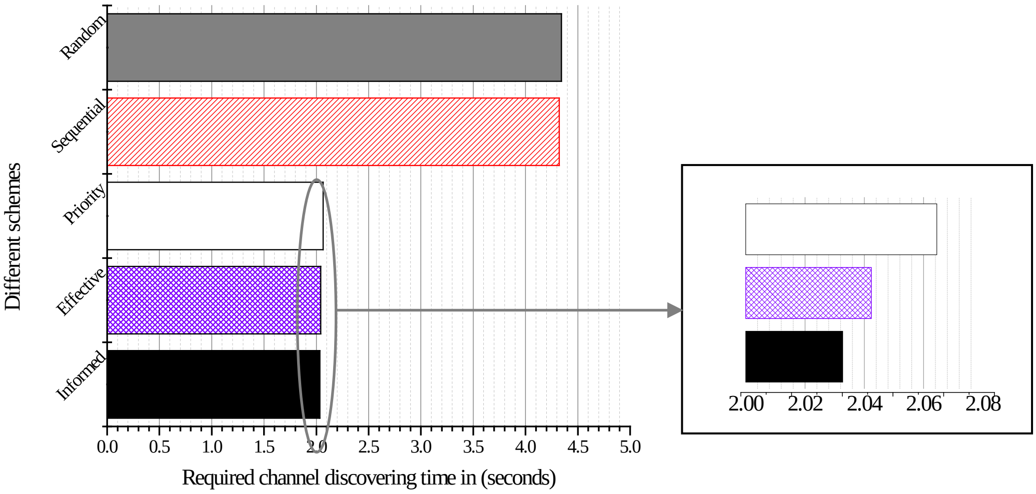

Fig. 6. Time taken for discovering a new idle channel during channel vacation.

Fig. 7 shows the time taken to switch channels as a function of the number of cooperative users, only for proactive discovery schemes. The switching time decreases as the number of users becomes greater because the probability of detection increases with the number of users. Furthermore, the Informed discovery scheme shows superior performance over the others. Nevertheless, the reduction in discovery time is very small when the number of users is greater than 10. In fact, T_{req}^{nc} converges to 2.02055 s, which is almost equal to the time taken to sense one channel (2.02001 s). This implies that the parameter r, in the minimization problem (6), is in the range $r > 1$, as 2.02001 s $\le T_{req}^{nc}$. In an earlier experiment, we have shown that $r \le 2$, which leads to the conclusion that $1 < r \le 2$. In other words, during channel vacation, SUs can discover a new idle channel after scanning one or two channels with the proposed scheme. Hence, SUs are not required to have more than two backup channels because they can achieve the goal of discovering a new idle channel with two or less backup channels in hand. This, in turn, minimizes the frequency of OB sensing required to keep track of all the backup channels. Consequently, the impact of the proposed scheme on the throughput is even smaller. As a final testament to our proposed scheme, we derived the cumulative distribution function (CDF) based on 1000 iterations for different combinations of idle-busy channels, showing the distribution of channel discovery time. The CDF is required when searching for a new channel and the number of cooperative users is 10 is shown in **Fig. 8**. As depicted in the graph, the probability of discovering a new channel with the Informed scheme is higher than that of the Effective and the Priority based approaches given in [22] and [23], respectively. Even though it is true that all schemes could find the new channel after a maximum of two scans, **Fig. 8** shows that the Informed scheme is significantly faster than the others. Therefore, we conclude that the proposed scheme is better than any other sensing scheme. With this in mind, we now illustrate the impact of the Informed scheme on achievable and aggregate throughput.

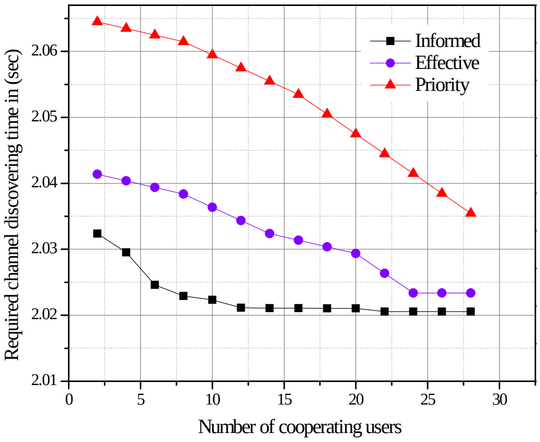

Fig. 7. Time required to discover a new channel as a function of the number of users.

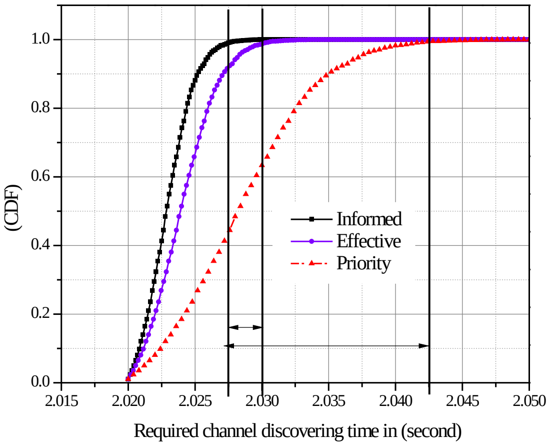

Fig. 8. CDF of channel switching time where the number of cooperating users is kept at 10.

In **Fig. 9**, we show that the effect of OB sensing on the achievable throughput per frame. As shown in the figure, the achievable throughput per frame degrades slightly when the OB sensing duration ω increases from 0 ms to 6 ms; however, this effect is insignificant. Specifically, the maximum spectral efficiency effect when $\omega = 6$ is less than 0.4 bits/s/Hz. In reality, 1 ms is enough to detect the presence of PUs on a channel and this translates to $\omega = 1$. In this case, the effect of OB sensing on the achievable throughput per frame is very small to be even considered as an effect. The achievable throughput per frame, in the absence of OB sensing (No_OB) corresponds to that reported in [8]. However, No_OB implies reactive sensing following channel vacation, which leads to a longer time of new channel discovery, as discussed earlier.

Finally, in **Fig**. **10,** we demonstrate the effect of OB sensing interval and OB sensing duration on aggregate throughput, as the time spent by SUs on an idle channel (T_{idle}^{cur}) increases. In this figure, "*With_OB_ I = 8* $\omega = 3$" is interpreted as OB frames occur every 8 frames and the time taken to sense the OB channel is 3 ms. The aggregate throughput increases linearly as T_{idle}^{cur} increases. Similarly, the aggregate throughput decreases very slightly because of the impact of OB sensing duration. However, this impact is negligible. CRs can, essentially, monitor OB channels frequently as long as the monitoring duration is small. From our numerical results, we have proven that, implementing our proactive OB sensing minimizes the time required to discover a new channel and its effect on throughput is insignificant.

Throughput reduction while operating on an idle channel has two benefits. Firstly, when PUs are detected on the channel, SUs can switch to a new idle channel instantly, enabling seamless communication in a CRN. Secondly, PUs will not suffer from interference due to the presence of SUs on their channel, and thus PUs and SUs coexist in harmony. In addition, because SUs can discover an idle channel quickly, using the proposed scheme, the throughput lost in discovering an idle channel can be made up for in the new channel, unless channel under-utilization stays free indefinitely, which cannot be the case. Therefore, it is beneficial to reduce the channel discovery time at the insignificant cost of SUs throughput reduction.

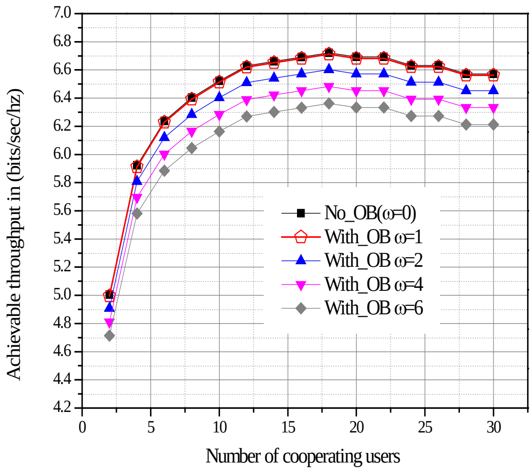

Fig. 9. Achievable throughput per frame as a function of the number of cooperating users and OB sensing duration ω in ms.

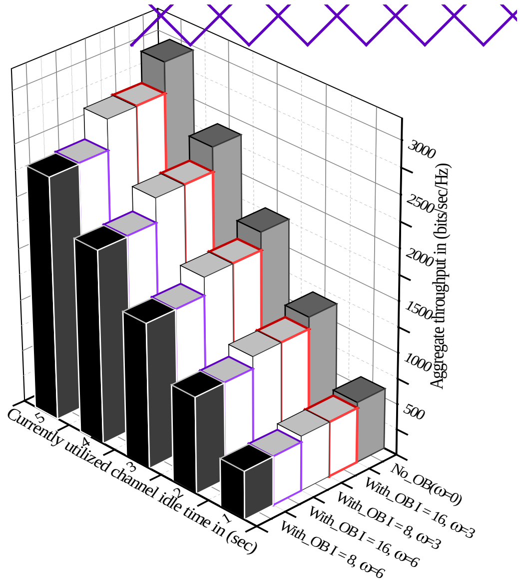

Fig. 10. Aggregate throughput for different OB sensing interval I; and OB sensing duration ω ms.

7. Conclusion

We have studied the usage of OB sensing to solve the problem of seamless communication in cognitive radio networks, and avoid interference with primary users. The main obstacle in providing seamless communication has been the time required to discover a channel after vacating the one used by the SUs. Our OB sensing scheme minimizes the time required to discover a new channel without degrading the throughput greatly. Because SUs have little time to spend on discovering a new channel, they can vacate a channel as soon as PUs appear, to avoid interference. To support our proposed scheme, we have presented our work through analysis. The results confirmed, using the Informed scheme, that non-utilized channel discovery can be carried out quickly and with very minor impact on throughput. Therefore, we can conclude that the Informed scheme can be used to avoid interference with PUs and provide seamless communication in CRNs. In the future, we would like to study the impact and benefit of proactive sensing through USRP. The implementation of our work on real life systems could give an insight into OB sensing or bring to the surface other issues to be investigated.

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