Priority Channel Selection Based on Detection History Database

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ABSTRACT

This paper proposes a new database-based two-stage channel selection method for cognitive radios. The proposed method consists of two stages, namely the database collection and signal detection parts. The database collects information about channels. When a cognitive radio needs to find an unoccupied channel for a transmission, it sends a query to the database. Based on the information collected to the database, the most probably unoccupied channels at requesting time are the best candidates when searching unoccupied channels, and these channels are submitted to the cognitive radio. The cognitive radio performs first the power level detection. Based on the power level information delivered from the database, a full signal detection is performed next to the channel with low enough power level to ensure that the channel is really unoccupied.

I. INTRODUCTION

New spectrum for applications such as a wide-band public safety communications is hard to find as most of the spectrum is already licensed to specific devices aka primary users (PU). To improve spectrum utilization and to enable new applications, cognitive radios [1] have been proposed to seek currently unoccupied radio channels in order to use these for flexible communication. Possible applications are, for example, different wireless devices including wireless internet, keyboards, microphones, etc. The goal is to allow locally unoccupied frequency channels (”white spaces”) originally reserved to some PUs to be used by secondary users (SU). The amount of white spaces varies over different channels, geographic locations and time, but it is widely known that the existing frequency allocation procedure suffers from the lack of efficient spectrum usage [2]. The white spaces can be located, for example, using geographic location monitoring, beacons, databases, or spectrum sensing [3], [4], [5], [6]. PU may send beacon signals in order to inform cognitive radio devices (CRD) about availability of channels. The problem with beacons is that the beacon may not reach all radio devices because of fading. The usage of database usually requires the possibility to estimate the location, for example, using the global positioning system (GPS). In both of these approaches, the problem is that the devices are not able to operate individually. Instead, in spectrum sensing, knowledge about the primary (neither other secondary) users is not required and the SUs may operate individually if needed. Therein, the CRD detects an unoccupied channel by completing a signal detection on the channel. When no signal is detected, the channel is interpreted as a free channel and the CRD can take the control of that channel. Usually, sensing is performed only once. However, sensing can be done using first coarse and secondly more sensitive fine sensing [7]. Typically, a reactive approach is used, i.e., the frequency channels are searched sequentially in some order until a free channel is found or all the channels are decided to be occupied. Usually, a simple random search order is assumed [8]. The problem is that if most of the channels are already occupied, the CRD needs to detect a large number of channels before an unoccupied one is found. This consumes both time and computational resources and is not very suitable for real-time applications. Prediction based on the past observations can be used, for example, to find channels having the longest idle times [9] or to enable proactive spectrum access [10]. Experience-based learning, understanding and problem solving called as case-based reasoning is considered, for example, in [11].

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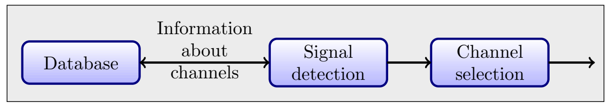

Fig. 1. The proposed system.

In this paper, a novel combination of spectrum sensing and database techniques (Fig. 1) is proposed and analyzed. In the proposed method, a database delivers information about the most probably unoccupied channels (channel candidates in the sequel) to the CRD so that it does not have to search channels in a random order. Channel candidate means a channel that is possibly free based on the detection history at the request time. The database also informs the CRD about power levels when the channel candidate has been earlier noticed to be free. After that, the CRD detects the occupancy of a channel candidate

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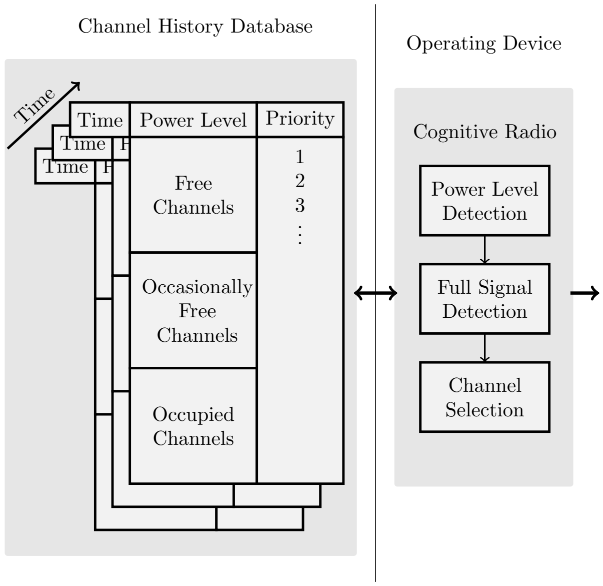

Fig. 2. Priority channel selection based on detection history database.

in two parts, using first simple and fast power level detection (PLD) and secondly more complex but accurate full signal detection (FSD). If the measured power level is low enough, PLD leads to the assumption that the channel candidate may be unoccupied, and FSD is performed to ensure that. The proposed method has several benefits. Both the time and computation resources are saved because only the most probably unoccupied channels are investigated and time consuming FSD is performed only if it really seems that the channel is unoccupied.

II. Proposed Channel Selection Method

The proposed method consists of two stages: signal detection and database as illustrated in Fig. 2. When a CRD wants to transmit, it sends a query to the database, which sends information about k best channel candidates to the CRD.

(1) Signal detection includes low-complex PLD and more complex but accurate FSD. The CRD performs PLD for the first channel candidate and compares the measured power level to the power level delivered by the database. If the measured power level is low enough, the channel candidate is determined to be possibly unoccupied and a FSD is performed to ensure this. If not, that channel candidate is skipped and the next channel candidate is searched. If all the k channel candidates were occupied, CRD sends a new query.

(2) The information from part (1) is used to update the database. Based on that information, the most likely unoccupied channels are the best candidates when searching unoccupied channels.

A. Signal Detection

The problem is how to measure which power level is low enough. This problem can be solved, for example, by determining a threshold that separates the noise levels into two sets: below the threshold are the noise levels corresponding the most probably unoccupied channels, and vice versa. If the measured power level is lower than the threshold, the channel candidate has a high probability to be unoccupied, and FSD is performed to ensure that. If the power level exceeds the threshold, the channel is skipped and PLD is performed to another channel candidate. The usage of PLD saves both time end computational efforts because the time consuming FSD is performed only if it really seems that the channel may be free, i.e., it is performed only to the unoccupied channel candidate. The PLD can be performed, for example, using a simple consecutive mean excision (CME) algorithm [12].

The PLD alone is not enough to decide if the channel is occupied or not because individual channels may have different background noise, for example. Thus, FSD is performed to the channel candidate which has been determined to be probably unoccupied. If FSD determines that the channel is unoccupied, transmission is allowed. Otherwise, PLD is performed to the next channel candidate. The used FSD method depends on the situation. If the detected signals are narrowband, the detection can be performed, for example, using simple energy detector aka radiometer [13] or without any *a priori* knowledge operating localization algorithm based double-thresholding (LAD) method [14]. If the detected signals are wideband, i.e., covering the whole system bandwidth, the detection can be performed, for example, using cyclostationary [15] or maximum-minimum eigenvalue (MME) based detector [16].

B. Database

A database is used to collect and share information of all channels. A database collects information including, for example, the channel number, the power level measurement results and the channel reservation status (occupied/unoccupied) in specific time instants. There can be also some other information, for example, PU's transmission timetables if those exists. The more information is stored to the database, the more memory it will require.

When a CRD needs to find an unoccupied channel, it sends a query to the database. Based on the stored (history) information, the database searches the channels that have earlier been unoccupied at that previous day in that time and, of course, to some time to future. Depending on the PUs, the occupancy of a channel may vary, for example, per day or week, and it may also vary between the channels. For example, the PU may be a television broadcaster that is broadcasting data only during certain period of the day. In many cases, the radio channel occupancy levels follows the same temporal pattern, therefore a channel that was occupied in the same time earlier, is most likely occupied also now. The database sends the information about k of the most probably free channels, including, for example, the number of the channel and the noise level. The k can be, for example, 3 or 5.

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The database is updated constantly. The updating can be done, for example, collecting feedback from CRD. In that case, the channel prediction accuracy is improved. In the beginning, CRD have to operate independently. Before the database has been created, the sensed channels are selected based on instantaneous information, for example, randomly. CRD performs both PLD and FSD and sends this information to the database. As the database has collected enough information, it can start to operate. In addition, if there are some problems with the database or the connection with the database is lost, CRD can continue operating independently.

It should be noted that the database can be used only locally. That is, several CRDs operating in the same geographical area (as in campus) can use a shared database, or every radio device may have its own database. Obviously, the more information is collected to the database, the more memory is required and the slower are the database searches.

III. Analysis

When the database is operating properly, it can greatly reduce the used time and computational efforts when compared to the classical unoccupied channel search strategies. Because the proposed method is robust for the amount of unoccupied/occupied channels, the more of the channels are occupied, the more benefit can be achieved. Next, the signal detection stage is analyzed. The proposed method is compared to the two well-known search strategies, namely the random search and sequential search [8]. In the random search, searched channels are chosen randomly. The history of the previously searched channels is taken into account, so each channel is sensed only once. The sequential search starts, for example, from the lowest frequency and continues searching to the higher frequencies. Note, that on average, the results for random and sequential search are equal, because the occupied channels are chosen randomly and there is no difference whether the sensing is performed in an sequential or random order. For simplicity, the delay caused by a database query is not taken into account here.

A. Perfect Sensing

Let us first assume that the first channel which PLD decides to be unoccupied is really unoccupied. In other words, FSD is performed only once (perfect sensing). Assume that when finding an unoccupied channel, the number of sensed channels is n. That is, $n-1$ channels have to be sensed before an unoccupied channel is found. Assume also that the sensing time of each channel is t_1 for PLD and t_2 for FSD. The random search performs only the FSD whereas the proposed method performs the both. Here it is assumed that there is no possibility to determine suitable threshold for PLD without "learning" via database usage. Otherwise, the random search could also use PLD before FSD to each channel to be detected. It could also be possible that the random search uses different kind of fast "pre-detector" before FSD but this is not considered here.

TABLE I
The values of x when the proposed method operates faster than random search. Perfect sensing is assumed, i.e., FSD is performed only once. n is the number of sensed channels and $x = t_1/t_2$.

$x = 1.0$	$-^*$
$x = 0.9$	$n > 10$
$x = 0.8$	$n > 5$
$x = 0.7$	$n > 3$
$x = 0.6$	$n > 2$
$x = 0.5$	$n > 2$
$x = 0.4$	$n > 1$
$x = 0.3$	$n > 1$
$x = 0.2$	$n > 1$
$x = 0.1$	$n > 1$

* never

In the random search, the number of sensed channels depends on the reservation status of the channels: the more occupied channels, the more channels have to be sensed before an unoccupied one is found. Mathematically, the number of sensed channels is [8]

$$n = \frac{N+1}{K+1}, \tag{1}$$

where N is the total number of channels and K is the number of unoccupied channels. Thus, for the random search, the total sensing time for n channels is

$$t_{rs} = nt_2 \text{ ms}. \tag{2}$$

In the proposed method, the variable n does not depend on the amount of unoccupied channels, i.e., the utilization rate. It depends only on the performance of the database: how well it is able to suggest unoccupied channels. The total sensing time per one channel is t_1+t_2, if the channel is decided to be unoccupied after PLD and t_1, if the channel is decided to be occupied after PLD. The sensing time for PLD can be expressed to be part of the sensing time for FSD, i.e., $t_1 = xt_2$. If perfect sensing is assumed, the total sensing time for n channels is

$$t_{prop} = (nx+1)t_2 \text{ ms}. \tag{3}$$

In the optimal case, $n = 1$, i.e., both PLD and FSD are performed once.

Let us investigate the situation when the proposed method operates faster than the random search. From (2) and (3), we get that the proposed method is faster than the random search when $nx+1 < n$. The values of x when the proposed method operates faster than the random search are presented in Table I. For example, when $x = 0.5$, the proposed method requires less time than the random search if $n > 2$. It means that when PLD uses half of the time of what FSD uses, the proposed method uses less time than the random search if the number of sensed channels is more than two. It can be seen that the smaller x is, the smaller n is required before the proposed method requires less sensing time than the random search. It should be noted that in practice, the difference between

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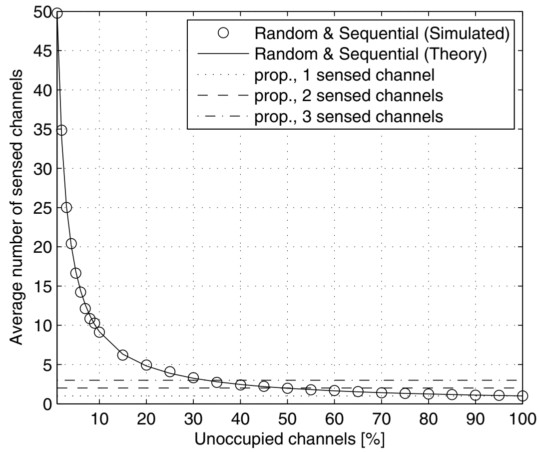

Fig. 3. Average number of sensed channels before an unoccupied channel is found vs. unoccupied channels [%]. The total number of channels is 100.

the sensing times of PLD and FSD should be large. Thus, it is realistic to assume that $x < 0.3$, at most. Therefore, it can be said that the proposed method is faster than the random search when the number of sensed channels $n > 1$, and the random search is faster than the proposed method when $n = 1$, respectively. From (1) it follows that in the random method, $n = 1$ only if $N = K$, i.e., all the channels are unoccupied. Thus, in every other situation, the proposed method requires less time than the random search. Note, that it is assumed that PLD performs properly, i.e., the channel decided to be unoccupied after PLD is really unoccupied, so FSD is performed only once.

The average number of sensed channels before an unoccupied channel is found vs. the number of unoccupied channels [%] is presented in Fig. 3. The proposed method is compared to the random search and sequential search. In the proposed method, three different variations are used: the unoccupied channel is found after 1, 2 or 3 sensed channels. Here, the total number of channels is $N = 100$, the occupied channels were chosen randomly, and the number of iterations was 1000. Therein, unity detection probability and zero false alarm probability are assumed, i.e., the channel occupancy is perfectly determined. Here, collisions etc. are not taken into account because these are mainly depending on the sensing method, not on the channel selection strategy. As expected, the less there are unoccupied channels, the worse is the performance of the random and sequential methods. For example, when there is only one unoccupied channel, it is found after 50 sensed channels, on average. Furthermore, if 10% of the channels are unoccupied, it will take on average 9 sensed channels before an unoccupied channel is found. This requires a lot of time and computing efforts. When 30% of the channels are unoccupied, the average number of sensed channels is equal, i.e., 3, for the proposed method in the case of 3 sensed channels and for both the reference methods. The corresponding percentage value for the proposed method in the case of 2 sensed channels is 50%. Instead, the reference methods achieve the best performance, i.e., detection after one sensed channel, only when all the channels are unoccupied. For example, assume that $t_1 = 0.03$ ms and $t_2 = 0.4$ ms. As shown in Fig. 3, the total sensing time of the proposed method does not depend on the channel occupancy situation, i.e., it is always the same. That is, from (3) we get that the total sensing time for $1/2/3$ channels is $0.43/0.46/0.49$ ms. In the case of random search, when only one channel is unoccupied, the total sensing time is 20 ms (2). That is, the random search requires about $40-46$ times more time than the proposed method. Respectively, when 10 % of the channels are unoccupied, the random search requires about $7-8$ more time than the proposed method. In the other hand, when all the channels are unoccupied, the total sensing time is 0.4 ms for the random search. It is slightly less than that of the proposed method, that is, $0.03-0.09$ ms. However, the difference is very small: it is only about $0.07-0.2$ times more than for random search. It should be noted that a database query causes some delay. So, $\sum_{i=1}^{m} \alpha_i$, where m is the number of database queries and α_i is the time of ith query, should be added to (3). This is highly dependent on the number of channel candidates k send per one query. The larger k is, the higher is the probability than only one query is required, i.e., $m = 1$.

B. Imperfect Sensing

Next, more realistic case when FSD is performed more than once is considered. Probabilities and delays are taken into account. Assume that the total number of channels is N and the PU is active in a channel i, $i = 1, \cdots N$ with probability λ_i. The sensing times are t_1 for PLD and t_2 for FSD. The PLD has false alarm probability P_F and detection probability P_D. The FSD is assumed to operate perfectly. The probability of finding an unoccupied channel when searching the first k channels can be found with

$$\vartheta_k = \vartheta_{k-1} + \left(\prod_{i=1}^{k-1} [(1-\lambda_i)P_F + \lambda_i] \right) (1-\lambda_k)(1-P_F). \tag{4}$$

In the case when λ_i equals to λ, $\vartheta_k = 1-[(1-\lambda)P_F+\lambda]^k$. For simplicity, assume that the probability of finding a free channel is close to one. Thus, the average number of times PLD is used for finding a free channel is

$$\eta_k = \eta_{k-1} + k \left(\prod_{i=1}^{k-1} [(1-\lambda_i)P_F + \lambda_i] \right) (1-\lambda_k)(1-P_F) \tag{5}$$

where $\eta_1 = (1-\lambda_1)(1-P_F)$. When λ_i equals to λ, $\eta_k = \frac{1-c^{k+1}}{1-c} - (k+1)c^k$, where $c = (1-\lambda)P_F + \lambda$. Furthermore, $\lim_{k\to\infty} \eta_k = 1/(1-c)$. When λ_i equals to λ, average number of times FSD is used for finding a free channel with

$$\varepsilon_k = d \sum_{n=1}^{k} \left(\sum_{i=0}^{n-1} (i+1) \binom{n-1}{i} [\lambda P_M]^i [\lambda P_D + g]^{n-1-i} \right) \tag{6}$$

where $d = (1-\lambda)(1-P_F)$ and $g = (1-\lambda)P_F$. The average delay in finding a free channel is $\tau_k = t_1\eta + t_2\varepsilon_k$.

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TABLE II
THE VALUES OF x WHEN THE PROPOSED METHOD OPERATES FASTER THAN RANDOM SEARCH. ρ/ν DENOTES THE UTILIZATION RATE, I.E., $\rho\%$ OF THE CHANNELS HAVE $\lambda_i = 0.9$ AND $\nu = 100 - \rho\%$ OF THE CHANNELS HAVE $\lambda_i = 0.1$. $N = 50$, $P_D = 0.8$ AND $P_F = 0.1$

ρ/ν	random	proposed method	prop. method better
$90/10\%$	$5.34t_2$	$1.23t_1 + 1.02t_2$	$\forall x$
$70/30\%$	$2.87t_2$	$1.23t_1 + 1.02t_2$	$\forall x$
$50/50\%$	$1.97t_2$	$1.23t_1 + 1.02t_2$	$x < 0.77$
$30/70\%$	$1.50t_2$	$1.23t_1 + 1.02t_2$	$x < 0.39$
$10/90\%$	$1.12t_2$	$1.23t_1 + 1.02t_2$	$x < 0.15$

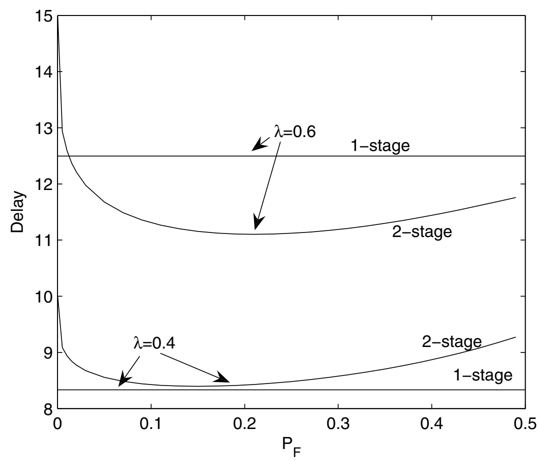

Fig. 4. Delay for finding a free channel. $N = 20$, $t_1 = 1$, $t_2 = 5$ and $\gamma = 5$ dB.

Assume that an energy detector is used. In the presence of Gaussian signals and Gaussian noise and using 2 real-valued samples, the detection probability is $P_D = P_F^{1+\gamma}$, where γ denotes the signal-to-noise ratio (SNR). Let us assume that there is $N = 50$ frequency channels. For the proposed method, $P_F = 0.1$ and $P_D = 0.8$ for the PLD. The results when the proposed method operates faster than the random search for different occupancy levels are presented in Table II. For example, if 30% of the channels have $\lambda_i = 0.9$ and 70% of the channels have $\lambda_i = 0.1$, the theoretical search delay for pure random search is $1.5t_2$ and for the proposed method $1.23t_1 + 1.02t_2$. Because $t_1 = xt_2$, we get that the proposed method is faster than the pure random search when $x < 0.39$. It can be seen that the less there are unoccupied channels (i.e., the larger ρ is), the more benefit the proposed method offers.

Next, pure FSD based detection (i.e., 1-stage) is compared to the proposed PLD+FSD-based method (i.e., 2-stage). In Fig. 4, delay for finding a free channel vs. P_F is presented when $N = 20$, $t_1 = 1$, $t_2 = 5$ and $\gamma = 5$ dB. The delays are presented for $\lambda = 0.4$ and $\lambda = 0.6$. It is confirmed that for higher λ, the proposed method offers smaller delays than pure FSD.

IV. CONCLUSIONS

In this paper, we have proposed a novel channel selection method for cognitive radios that combines database and spectrum sensing. The database delivers to the cognitive radio device information about the most probably unoccupied channels, and the cognitive radio device ensures the reservation status of the channel by making low-complex power level detection and, when needed, a more complex full signal detection. Because the power level detection can be done much faster than full signal detection, the latter one is performed only to the channel which is most likely unoccupied based on the power level measurements. This saves both time and computational resources still maintaining reliable sensing results. It was shown that the method offers benefit over random channel search especially when there is a lot of occupied channels. However, it should be noted that the performance of the proposed method is highly dependent on the validity of the information given by the database.

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