ABSTRACT

Cognitive radios and flexible spectrum use (FSU) provide an efficient way to exploit underutilized radio spectrum by allowing secondary users to access licensed frequencies in an agile manner with the constraint that the licensed user will not be interfered. In order to identify such spectral opportunities, spectrum sensing is needed by the secondary users. In this paper a cooperative spectrum sensing policy employed by spatially displaced multiple cognitive radios is proposed. It enables sensing of multiple potentially discontinuous frequency bands simultaneously and facilitates mitigating the effects of shadowing and fading through spatial diversity.

Index Terms— Cognitive radio, Spectrum sensing, Frequency hopping, Spatial diversity.

1. INTRODUCTION

The useful radio spectrum has become a scarce resource. Spectrum measurement campaigns have shown that this is mostly due to the inefficient allocation of radio spectrum rather than the actual amount of wireless traffic [1]. The purpose of cognitive radio [2] is to find and exploit the underutilized radio spectrum by allowing secondary users (SU) to access the licensed frequencies whenever it will not interfere with the primary system. Therefore, spectrum sensing is needed by a cognitive radio system to identify such spectrum opportunities and to characterize the possible interference levels to the primary system. A spectrum opportunity in [3] is defined as a situation where there is such free spectrum that a secondary transmitter–receiver pair could use for their communication so that interference from the secondary transmitter to the primary receiver will be below an allowed level, and the interference from the primary transmitter to the secondary receiver will also be at an acceptable level needed for reliable communication.

SUs may be seen to form a wireless sensor network where spatial diversity may be exploited to improve spectrum sensing performance. When the sensors that are sufficiently displaced from one another diversity gains may be obtained via cooperation, since it is unlikely that all of them would be in a deep channel fade. The paybacks from spatial diversity to signal detection have been illustrated for example in [4], [5], [6].

Spectrum sensing policies have been proposed in the literature [7], [8], [9], [10], [11] for selecting the subband to be sensed at a given time. Most of the solutions are based on optimizing the secondary system throughput under the assumption that the behavior of the primary users may be described with a Markovian state model. For some wireless systems such as WLAN there is evidence that a Markovian model is a reasonably good assumption describing the dynamic behavior of the users, but generally this may not be the case. Also, the Markov model does not easily allow for incorporating different time scales of the primary system such as the peak hours.

In this paper a collaborative method for sensing simultaneously multiple subbands is proposed. A sensing policy that guarantees a desired diversity order and allows for maximizing the scanning speed of the whole set of subbands is introduced. By the term diversity order \( D \) we refer to the number of SUs sensing the same frequency band simultaneously. The design of the sensing policy is converted to designing and allocating pseudorandom frequency hopping codes to the spectrum sensors. The proposed method facilitates sensing simultaneously multiple potentially discontinuous bands that may have different bandwidths or may overlap in a straightforward manner. The frequency bands of interest are scanned by constellations of \( D \) SUs so that all sensing constellations are used over time. Consequently, the constellations will discover spectrum opportunities simultaneously yielding faster and therefore more efficient exploitation of the free spectrum. Constellations are \( D \)-tuples where \( D \) denotes the desired diversity order. The proposed method also allows for optimizing the selection of the sensed channels based on the observed occupancy statistics of the spectrum and the obtained throughputs.

This paper is organized as follows. The system model for cooperative sensing based on frequency hopping is described in section 2. In section 3 we give an example design of the frequency hopping code allocation for \( D = 2 \) given the number of SUs and number of subbands. In section 4 we present the simulation results of frequency hopping based cooperative sensing using the NS2 [12] network simulator and Matlab. The paper is concluded in section 5.

2. SYSTEM MODEL

The licensed radio spectrum of interest for the cognitive radio system may be very wide and even discontinuous. To facilitate easier receiver front–end design it may be more practical to subdivide the whole band into subbands that are sensed separately, instead of sensing the whole spectrum of interest at once. Alternatively, the band of interest may already consist of multiple subbands of different bandwidths scattered in the radio spectrum depending on the allocation of the bands to different operators. In this paper we assume that the cognitive secondary network consists of \( N_S \) wireless terminals that are sensing whether \( N_P \) primary users (PU), each occupying one particular frequency band, are active or not.
Wireless signals are exposed to slow and fast fading caused by large objects in the signal path and multipath propagation of the signal, thus making it harder to detect them. To combat against fading we assume that the SUs are sensing the spectrum collaboratively so that each subband is sensed simultaneously by at least $D$ SUs. Hence the SUs are assumed to be synchronized so that they see the same temporal radio spectrum.

After each sensing instant the SU sends its local test statistics (or binary decision) to the fusion center (FC) via a common control channel. The local statistics are then combined at the FC to make a global decision about the availability of the spectrum. The FC can be one of the SUs or a part of the network infrastructure.

3. PSEUDORANDOM FREQUENCY HOPPING BASED SENSING POLICY

In this paper a cooperative pseudorandom (deterministic) frequency hopping policy is proposed for spectrum sensing in cognitive radios. In the pseudorandom policy the band to be sensed in each sensing instant is predefined by carefully designed frequency hopping sequences. For the rest of the paper the terms frequency hopping sequence and frequency hopping code are used interchangeably. Frequency hopping code assignment for the SUs is made such that after each scanning period different $D$-tuples of the $N_S$ SUs will be employed to scan the spectrum of interest. In order to scan as much spectrum as possible at once, different $D$-tuples sense different subbands simultaneously. Table 3 shows an example design of the hopping codes for $N_S = 4$, $N_P = 3$ and $D = 2$.

<table>
<thead>
<tr>
<th>Sensing instance</th>
<th>Code period</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU0: 1 2 3 1 2 3</td>
<td>F</td>
</tr>
<tr>
<td>SU1: 1 2 3 2 1 3</td>
<td></td>
</tr>
<tr>
<td>SU2: 2 3 1 2 3 1</td>
<td></td>
</tr>
<tr>
<td>SU3: 2 3 1 2 3 1</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Pseudorandom frequency hopping codes for $N_S = 4$, $N_P = 3$ and $D = 2$. At each sensing instance the SU senses the subband pointed by the current entry of its hopping code. Hopping code entries are pointing to the physical frequencies that are maintained in table $F$.

In frequency hopping based sensing each SU hops according to its hopping sequence to sense one of the subbands of interest. The subband to be sensed at time index $i$ is given by $f(i) = F[S_q(i)]$, where $S_q(i)$ is the $q$th frequency hopping sequence, $F$ is the table containing the mappings to the physical subbands. Table $F$ could include links to the subbands’ center frequencies and bandwidths. As $F$ is primary system dependent mapping to the physical frequencies, it may be assumed to be the same for all SUs exploiting the same primary network. However, frequency reuse in cellular primary systems would make the $F$ to be also location dependent, but for simplicity we assume that licensed frequencies are not reused. Hence the examination of hits between SUs sensing may be limited to the examination of hits between their frequency hopping sequences $S_q(i)$.

Assuming that all subbands have equal potential benefit to the SUs, the frequency hopping codes should be full, i.e., each subband is sensed equally often. However, the secondary network might posses prior knowledge of the subbands’ availability, throughput or the persistence of unoccupied spectrum over time in a specific location. Then SUs should sense less frequently those subbands that are occupied most of the time or that cannot provide adequate throughput. A simple way to do this in the frequency hopping based sensing is to map such less interesting subbands to the more interesting ones, so that they will be sensed more frequently. As the physical center frequencies are listed in the mapping $F$, these kind of priorities can be built inside the mapping by making more than one of the entries in the table to point at the same physical subband.

In a situation where two SUs wish to communicate it is import that they find a spectrum opportunity simultaneously in order to exploit it instantly. One way of ensuring this is to assign the SU pair that wishes to communicate always sense the same subbands simultaneously [3]. In our approach this means that they would be allocated the same frequency hopping code guiding which bands are sensed and when. When an unoccupied band is discovered, the secondary transmitter could transmit a request-to-send (RTS) message to the receiver. If the receiver has verified the band to be free it would then reply with a clear-to-send (CTS) message. This allows them to find out the channel quality simultaneously, and the FC could then grant them permission to use the channel based on its scheduling rule. Those SUs that have no desire to transmit or receive data may collect information on the state of the radio spectrum for the secondary network and provide the additional diversity needed in detecting the PU activity. They could also focus on finding spectral opportunities in other bands, hence speeding up the spectrum sensing over all subbands of interest.

3.1. Frequency hopping sequences

Next, design examples of the subband sensing patterns providing the desired diversity order are shown. The patterns are orthogonal hopping sequences that may be generated by applying cyclic shifts to any full sequence of integers. By orthogonality we mean that the codes can be phased so that all codes in the code family will be pairwise non-overlapping. The desired diversity order and consequently the number of hits among the SUs may be obtained by assigning the users in each $D$-tuple to have the same hopping code for one full code period. Instead of using cyclic shift sequences other code designs known in the frequency hopping spread spectrum (FHSS) literature could be applied.

The simplest way to generate a orthogonal code family is to cyclically shift any full sequence of integer numbers. Cyclic shifts may be generated by the modulo operation as

$$S_q(i) \equiv i + q \mod N_P,$$

where $q, i \in [0, N_P - 1]$.

The maximum periodic Hamming [13] correlation between any two codes in the family is $N_P$ and the minimum 0. The delays between every cooperating $D$-tuple can be adjusted so that minimum periodic Hamming correlation will be obtained.

3.1.1. Example of frequency hopping sequence assignment for $D=2$

Next, an example of the frequency hopping code allocation for the pseudorandom scheme for diversity order $D = 2$ is given. Desired diversity order over all subbands of interest is guaranteed by assigning each SU pair to hop according to the same frequency hopping sequence. After each full scan over the subbands the pairs are changed so that over time all sensing constellations will be covered. When SUs join the network, the FC assigns them to certain frequency hopping sequences according to a predefined code index table. In the
code index table the indices are arranged so that over time all D-tuples of $N_S$ SUs are considered, which corresponds to an all-play-all round-robin tournament design [14] in case $D = 2$. Table 2 illustrates the simplest round-robin hopping sequence index table for $N_S = 4$.

<table>
<thead>
<tr>
<th>time $\rightarrow$</th>
<th>SU$_0$: $S_0$ $S_0$ $S_0$</th>
<th>SU$_1$: $S_0$ $S_1$ $S_1$</th>
<th>SU$_2$: $S_1$ $S_0$ $S_1$</th>
<th>SU$_3$: $S_1$ $S_1$ $S_0$</th>
</tr>
</thead>
</table>

Table 2. Round-robin frequency hopping code index table for 4 SUs. The code assignment corresponds to the hopping sequences shown in table 3. Each entry in the table corresponds to one hopping code in the selected code family, i.e., one full scan of the spectrum.

Round-robin tournaments for arbitrary $N_S$ and $D = 2$ are well know [14]. However tournament tables that go through all possible D-tuples for arbitrary $D$ and $N_S$, need to be searched using computer based methods. However, since the hopping codes can be stored into the SUs in advance, the search can be done off-line.

### 3.2. Random hopping

Finally, we briefly analyse the random hopping scheme used in the simulations for comparison purposes. In random hopping each SU selects the subband to be sensed randomly according to some pre-defined probability density function. Random hopping may be attractive in some cases where the number of subbands is significantly lower than the number of SUs sensing them.

The realized diversity order $D$ in random hopping is also a random quantity, and the desired diversity order may be achieved on average only over a long period of time. For uniformly distributed random hopping the probability of having exactly $D$ SUs sensing the same subband simultaneously is binomially distributed. The expected value for $D$ is then $E[D] = \frac{N_S}{N_P}$ and the variance is given by $\text{var}(D) = \frac{N_S}{N_P}(1 - \frac{1}{N_P})$, where $N_S$ is the number of SUs and $N_P$ the number of subbands.

### 4. SIMULATION EXAMPLES

The simulations of the detection performances of the pseudorandom and random frequency hopping schemes were carried out using the NS2 network simulator. Matlab was used to extract numerical results from the NS2 outputs.

In this paper we consider the single dedicated FC scenario, although the proposed method is equivalently suitable for the scenario with individual FCs. In the simulations the mean SNR of the primary signal for all SUs was equal, which roughly corresponds to a situation where the primary transmitter is far away from the SUs.

The primary signal is assumed to undergo both shadow and Rayleigh fading. Both fadings are simulated as block fading channels, i.e. the received signal at the $t$th SU is $y_t(t) = h_t x(t) + w_t(t)$, where $t$ is the time index, $h_t$ is the channel from the primary transmitter to the $t$th SU, $x(t)$ is the transmitted primary signal and $w_t(t)$ is zero-mean Gaussian thermal noise. Channel $h_t$ contains both shadow and multipath components multiplicatively and also the pathloss.

The employed cooperative spectrum sensing scheme is cyclostationary detection from [15]. This detector is a constant false alarm rate (CFAR) binary detector, where the global decision is made in the FC by summing the received LLRs (Log-Likelihood Ratio) from different SUs. This can be done under the assumption that the LLRs are conditionally independent. The detectors in the simulations use the OFDM symbol frequency and delay $T_D$, where $T_D$ is the length of the useful symbol data in an OFDM symbol. The constant false alarm rate is set to $P_{fa} = 0.01$. The number of subbands is $N_P = 10$ and we assume that each subband may be occupied by one PU at a time.

Fig. 1 shows the mean probability of detection ($P_d$) as a function of the mean SNR for the pseudorandom hopping and random hopping schemes. The primary signal is DVB-T signal and the signal length used for sensing is 20 OFDM symbols. The number of SUs is in the random hopping cases are 4, 10 and 20. It can be seen that when the number of SUs is less than the number of PUs it is not very likely that random hopping will result into two or more users to sense the same subband simultaneously. In case with $N_S = 20$ the average diversity over a long period of time will be 2. However, for shorter time periods, the performance varies a lot. Since in the pseudorandom hopping the diversity order is kept at a specified constant $D$, the probability of detection would not change as the number of SUs is varied between $D \leq N_S \leq D N_P$. When the number of secondary users increases, the whole set of subbands is scanned faster with the same detection performance.

Since increasing the number of SUs sensing each band slows down the scanning of the whole spectrum of interest, we should justify the employment of diversity in the spectrum sensing. The scanning speed of the pseudorandom hopping with diversity order $D$ may be quantified as $1/D$. Then the overall detection speed may be evaluated as $1/(D T_D)$, where $T_D$ is the needed signal length to detect signals at certain SNR with a target probability of detection $P_{d,target}$. Fig. 2 illustrates the effect of the diversity order on the overall detection speed when we want to detect WLAN signals with $P_{d,target} = 0.9$ at SNR$= -21$ dB at each subband. When $D T_D/T_S < 1$, it means that sensing over multiple bands with diversity order $D$ is faster than sensing with $D = 1$. In fading channels the gain from diversity is evident. For the AWGN channel the increase in the overall scanning time when increasing $D$ is greater than the reduction in the sensing time required to reach the desired detection probability. This is not surprising since in the AWGN channel diversity arises specifically from having more independent samples. Moreover, due to the fusion rule of the employed detection scheme the relative detection speed deteriorates in AWGN channel as $D$ increases.

### 5. CONCLUSIONS

In this paper a cooperative spectrum sensing policy for sensing multiple frequency bands simultaneously in a cognitive radio system is proposed. A pseudorandom frequency hopping based cooperative sensing scheme exploiting spatial diversity among SUs is proposed. It has been demonstrated that cooperative spectrum sensing with pseudorandom frequency hopping has the following assets:

- It guarantees a desired diversity order to mitigate the effect of shadowing and fading.
- It allows easy pairing of secondary transmitter and receiver that want to communicate so that they find spectral opportunities simultaneously.
- It facilitates sensing multiple potentially discontinuous bands of different bandwidths in a straightforward manner.
order may be achieved on average over a long period of time. The pseudorandom scheme is able to guarantee the desired diversity order, whereas for random hopping diversity order may be achieved on average over a long period of time. The pseudorandom scheme guarantees that each subband is sensed by every SU within one hopping code period. This speeds up the detection of possible hidden nodes, when only one or few SUs have an unobstructed channel to the primary transmitter.

6. REFERENCES