Matched filter detection with dynamic threshold for cognitive radio networks
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Abstract—In cognitive radio networks, spectrum sensing aims to
detect the unused spectrum channels in order to use the radio
spectrum more efficiently. Various methods have been proposed
in the past, such as energy, feature detection, and matched filter.
These methods are characterized by a sensing threshold, which
plays an important role in the sensing performance. Most of the
existing techniques used a static threshold. However, the noise is
random, and, thus the threshold should be dynamic. In this paper,
we suggest an approach with an estimated and dynamic sensing
threshold to increase the efficiency of the sensing detection.
The matched filter method with dynamic threshold is simulated and its
results are compared to those of other existing techniques.

Keywords—cognitive radio networks; spectrum sensing; energy
detection; matched filter detection; autocorrelation based sensing;
estimated dynamic threshold

I. INTRODUCTION

The use of smart devices has exponentially increased over
the last decade, which resulted in an increase of spectrum
channels demand. However, radio spectrum is a finite resource
[1]. Some channels are highly used while others are sparsely used
which caused a great spectrum scarcity. Studies have shown that
there is significant scope of improving spectrum utilization [2].
One of the solutions proposed to address the spectrum scarcity
problem is cognitive radio. This technology allows unlicensed
users, secondary users (SU), to use the radio spectrum channels
allocated to licensed users, primary users (PU), when the
channels are temporarily not being utilized by the PUs.
According to Mitola [3], cognitive radio is an intelligent radio
frequency transmitter/ receiver designed to detect available
channels in a wireless spectrum and change transmission parameters enabling more communications and improving radio
operating behavior.

One of the important functions in a cognitive radio is
spectrum sensing, which allows an SU to detect the presence or
absence of PU transmission in licensed frequency bands, and
allow the SU to borrow unused spectrum from the PU. A number
of sensing techniques have been proposed over the last decade
[4]. These techniques are classified into two categories:
cooperative sensing and non-cooperative sensing [5, 6]. The
non-cooperative sensing category is sub-divided into three
subcategories: energy, feature, and matched filter based sensing.
Energy detection is the simplest technique which does not
require any information about the PU signal to operate. It works
by comparing the received signal energy with an estimated
threshold which depends on the noise power [7]. Correlation
based sensing is a method based on the value of the
autocorrelation coefficient of the received signal and exploits the
autocorrelation features that exist in the transmitted signal and
and that are not present in the noise [8, 5]. Matched filter based
sensing is a coherent pilot sensor which detects known PU
signals. It maximizes the signal to noise ratio (SINR) at the output
of the detector, but it requires a prior knowledge about the PU
signal. Thus, it is assumed that the PU transmitter sends a pilot
stream simultaneously with the data and the SU receiver has a
perfect knowledge of the pilot stream to verify its transmission
at the frequency band [1].

Sensing threshold is an important parameter in spectrum
sensing. When a detector does not properly adjust its threshold,
the sensing performance is degraded. A number of approaches,
based on energy detection, were proposed [11-16]. As the
sensing performance is highly affected by the estimation error
of noise power, a dynamic estimation style of noise power is
recommended in [11]. Adaptive threshold control is
implemented in [12] with linear adaption of the threshold based
on signal to interference plus noise ratio (SINR). This approach
attains a considerably higher SU throughput than the fixed
threshold approach, but maintains unacceptable false alarms.
Adaptive threshold in unknown white Gaussian noise is
presented in [13] with noise power estimation, keeping the false
alarm rate at a preferred point under any noise level. It is based
on a concept of a dedicated noise estimation channel in which
only noise is received by SU. An improved energy detection
method is proposed in [14], where misdetection of PU
transmission due to sudden drop in PU transmission power is
addressed by keeping an additional updated list of the latest
fixed number of sensing events that are used to calculate an
average test statistic value. A double-threshold technique is
proposed in [15] with the aim of finding and localizing
narrowband signals. Another technique is presented in [16]
based on wideband spectrum sensing, which senses the signal
strength levels within several frequency ranges to improve the
opportunistic throughput of SU and decrease the interference to
the PU.

In [7], each pair of \((P_d, P_f)\) was associated with a particular
threshold to make sensing decision. In [17], the sensing

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threshold is determined dynamically by multiplying the theoretical threshold by a positive factor. Several papers do not mention how the threshold was selected. However, with a static threshold, the sensing decision is not reliable because of the uncertainty of the noise. In this work, we suggest an estimated and dynamic sensing threshold for energy detection, matched filter detection and correlation based detection to increase the probability of detection and the decision reliability.

To evaluate the performance of spectrum sensing techniques, several metrics were used, including the probability of detection, $P_d$, and the probability of false alarm, $P_f$. $P_d$ is the probability that the SU declares the presence of a PU signal. The higher the $P_d$, the better the PU protection is. $P_f$ is the probability that SU declares the presence of PU when the spectrum is idle. The lower the $P_f$, the more the sensing method is effective in detecting the signal [4].

The remaining of this paper is organized as follows. In section II, we describe the sensing methods. In section III we explain the simulation methodologies for each method. The results of this simulation are discussed in section IV. Finally, the conclusion is given in section V.

II. SPECTRUM SENSING TECHNIQUES

Spectrum sensing allows the cognitive radio users to learn about the radio environment by detecting the presence of an event using one or multiple sensors. It consists in detecting the PU signal transmission in a given time to make decision to transmit in a frequency band [7]. The spectrum sensing model can be formulated as follows

\[
\begin{cases} 
  y(n) = h \ast s(n) & H_0: \text{PU absent} \\
  y(n) = h \ast s(n) + w(n) & H_1: \text{PU present}
\end{cases}
\]

where $n=1,...,N$, $N$ is the sample number, $y(n)$ is the SU received signal, $s(n)$ is the PU signal, $w(n)$ is the additive white Gaussian noise (AWGN) with zero mean and variance $\sigma_w^2$. $h$ is the complex channel gain of the sensing channel, $H_0$ denotes the PU signal is absent, and $H_1$ denotes the PU signal is present. The output $T$ of the detector is compared to a threshold to make the right decision

- if $T \geq$ threshold then PU signal is present
- if $T <$ threshold then PU signal is absent

If PU signal is absent, SU can start to transmit its streams; if not, SU does not transmit or stops its transmission. Fig. 1 presents the general model of spectrum detection.

![Fig. 1. General model of spectrum sensing.](image)

This model was used for all techniques; for each technique we changed the spectrum sensing method block.

A. Energy detection method

The decision statistic of an energy detector can be calculated from the squared magnitude of the FFT averaged over $N$ samples. The output is the received signal energy called the test statistic $T_{ED}$ as given by

\[
T_{ED} = \sum_n y(n)^2
\]

where $n=1,...,N$, $N$ is the sample number, $y(n)$ is the SU received signal.

The two performance metrics ($P_d$, $P_f$) can be evaluated using the central limit theorem when $N$ is larger than 250 ($N > 250$) to approximate the test statistics as a Gaussian. These two probabilities are given by

\[
P_d = Q \left( \frac{\lambda - N\sigma^2}{\sqrt{2N}} \right)
\]

\[
P_f = Q \left( \frac{\lambda - N\sigma^2}{\sqrt{2N}} \right)
\]

where $Q$ is the Q-function, $\lambda$ is the sensing threshold, $\gamma$ is the SNR, $\hat{\lambda}$ is the average threshold $\lambda = \frac{\lambda}{\delta_w^2}$.

The sensing threshold depends on noise power. It is expressed for a target $P_f$ as

\[
\lambda = \left( Q^{-1}(P_f) \sqrt{2N} + N \right) \delta_w^2
\]

Thus, the energy detection technique is sensitive to the noise uncertainty; however, its implementation is very simple [7].

B. Matched filter detection with an estimated threshold

It is the optimal filter that projects the received signal in the direction of the pilot $x_p$ [10]. The test statistic is given by

\[
T_{MFD} = \sum_n y(n) x_p^*(n)
\]

The test statistics $T_{MFD}$ is compared with a particular threshold to give the decision. $T_{MFD}$ is a Gaussian random variable and a linear combination of Gaussian random variables. According to the Neyman-Pearson criteria [7], $P_d$ and $P_f$ are expressed as

\[
P_d = Q \left( \frac{\lambda - E}{\delta_w^2} \right)
\]

\[
P_f = Q \left( \frac{\lambda}{\delta_w^2} \right)
\]

where $E$ is the PU signal energy. Sensing threshold is giving as a function of PU signal energy and noise variance

\[
\lambda = Q^{-1}(P_f) \sqrt{E \delta_w^2}
\]

Assuming that the signal is completely known as unreasonable and impractical, some communication systems contain pilot stream or synchronization codes for channel estimation and frequency band sensing. A hybrid matched filter structure is proposed in [18] based on traditional matched filter by mixing the segmented matched filter and the parallel matched filter to overcome the frequency offset sensitivity. This structure permits the balance between sensing time and hardware complexity. As both carrier frequency offset (CFC) and phase
noise (NP) denote the sensing performance of matched filter detection, in [19] matched filter detection performance is examined in presence of CFC and PN, and robust sensing techniques are proposed to overcome the negative impact of CFC and NP on detection performance.

C. Autocorrelation based sensing

In signal processing, for a given signal \( s(t) \), the autocorrelation function is defined as [9]

\[
R_{ss}(\tau) = \int_{-\infty}^{\infty} s(t) \cdot s^*(t - \tau) \, dt
\]

The sensing decision is based on the knowledge of the statistical distribution of the autocorrelation function. For random noise, the first lag of the autocorrelation is very small or negative, but when there is a signal, the autocorrelation at the first lag represents a significant value. Thus the sensing method consists of comparing \( R_{lag0} \) and \( R_{lag1} \) of the autocorrelation if the received signal and sensing decision is made as following:

- if \( lag0 >> lag1 \)  
  PU transmission is absent
- if \( lag0 \approx lag1 \)  
  PU transmission is present

Correlation threshold is the margin between the two lag values, for example, \( lag0 \) is superior to \((\lambda, \%)\) of \( lag1 \), where \( \lambda \) is a percentage value that represents a decision margin [3].

III. SIMULATION METHODOLOGY

In our work, three detection methods are implemented following a specific methodology for each one. The general simulation model is presented in Fig. 2. PU signal is generated as a QPSK signal with \( N \) samples. The AWGN channel adds white Gaussian noise to the input signal with the same number of samples \( N \). This random noise is generated according to the SNR range value and the input signal power. After the spectrum sensing method is applied to the output \( y(n) \), the test statistic is calculated according to each sensing method and compared with the estimated dynamic threshold. Based on this comparison, the sensing decision is made.

For the threshold estimation block, the threshold is estimated dynamically at each iteration, and multiplied by a threshold factor to see the impact of the threshold on detection performance. For each method, the threshold is estimated and then generated dynamically to perform the test comparison. An estimated dynamic threshold \( \lambda' \) is also used to simulate \( P_d \) and \( P_f \) for several values of \( SNR \) and sample number, which can be a strong point for our simulation results. \( \lambda' \) is giving as

\[
\lambda' = k \cdot \lambda
\]

where \( \lambda \) is the estimated threshold based on each sensing method algorithm and \( k \) is a positive factor.

\( P_d \) and \( P_f \) are used to evaluate the performance of each sensing technique. The simulation process is done for a number of iterations which is called cycle number and it represents the total number of experiments. \( P_d \) is simulated as the ratio of the total number of detections, \( N_d \), by the total number of experiments \( N_e \). \( P_f \) is simulated as the ratio of the total number of times the signal is not detected, \( N_f \), by the total number of experiments \( N_e \). These two probabilities are given by

\[
P_d = \frac{N_d}{N_t}
\]

\[
P_f = \frac{N_f}{N_t}
\]

To evaluate the performance of a given technique, the simulation process, shown in Fig. 3, is implemented and simulated for \( N_e \) experiments to get \( P_d \) and \( P_f \). At each iteration and for each sensing parameter, a variable count which is initialized to zero is incremented by one at each iteration. If the test statistic is greater than the sensing threshold, a variable count which is initialized to zero will be incremented by one. At the end of the loop, after \( N_e \) experiments, the total number of detections \( N_d \) is the total number of \( n \) values and \( N_f \) is the total number of \( m \) values, so the probability of detection \( P_d \) and probability of false alarm \( P_f \) are the average value over \( N_e \) experiments.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.pdf}
\caption{Simulation algorithm for spectrum sensing methods.}
\end{figure}

The model inputs are

- Sample number is chosen as the number of samples that gives maximum value of \( P_d \).
- Total number of experiments: 1000 cycles.
- SNR range: -20dB to +20dB.
- Threshold factors: 1, 2, 3, 4.

For each parameter setting, the outputs, \( N_d \) and \( N_f \) are obtained by varying \( SNR \), or threshold, or number of samples. Afterwards, \( P_d \) and \( P_f \) are calculated for the different \( SNR \) values, \( N_t \), and threshold.

In this paper, we chose to present the matched filter detection, detailed methodology and simulation using an estimated dynamic threshold approach. At each iteration of the loop, matched filter detection is done by convolving the received signal with some PU pilot stream, the output is averaged over \( N \) samples to get the test statistics \( T \) as shown in Fig.4.
Fig. 4. Simulation model for matched filter detection.

To estimate the sensing threshold, we used the quite time approach which refers to the time period when it is assumed that PU signal is absent and only noise is transmitted. Sensing threshold is given by

$$\lambda = \sum_{n=1}^{N} w(n)x_p^2(n)$$  

(14)

where $$\lambda$$ represents the estimated threshold value, $$n=1…N$$, $$N$$ is the sample number, w(n) is the additive white Gaussian noise, $$x_p^2(n)$$ is the PU pilot stream. At each iteration, the threshold value is generated dynamically using the quit time approach and multiplied by a threshold factor (1 to 4) to investigate the impact of the threshold on the performance of the sensing technique.

IV. RESULTS AND DISCUSSION

The results of the performance of the matched filter were compared to those of energy detection and autocorrelation techniques. To compare the three methods, simulations were done using the same parameters and varying SNR, threshold and number of samples N. Fig. 5 shows $$P_d$$ as a function of SNR for the three aforementioned sensing techniques. In this simulation $$N=1000$$, and the threshold factor =1.

As one can see, $$P_d$$ increases with SNR. For SNR values higher than 0dB, $$P_d$$ is higher than 90%. Under high SNR values, in which the signal is higher than noise, matched filter detection achieves its 100% of detection with a small number of samples while energy detection presents a very high probability of detection. However, false alarm is very high for energy detection, which means that this detector is not able to distinguish between noise and signal. Autocorrelation based sensing presents a lower probability of detection comparing to the other methods. However, the lack of false alarm data does not allow us to compare the performances of the three sensing techniques.

To summarize, in order to obtain a good detection, each method has a particular behavior under certain environment conditions. For energy detection, it gives a good performance under high SNR values, and, thus works best only for high power signals, high threshold, and high number of samples. However, this method is not reliable because of the non-ability to distinguish between noise and signal after detection. On the other hand, matched filter sensing achieves a high performance for low sample number and can work under low SNR values. For the autocorrelation based detection, the results give low $$P_d$$ under low SNR compared to the others methods.

In the second experiment, we focused on matched filter detection results. The simulation is done for 1000 experiments to get an average result of $$P_d$$ and $$P_f$$ for each set of parameters.

Fig. 6 represents $$P_d$$ as a function of N for several values of SNR. For higher SNR ($$\geq$$ 4dB), $$P_d$$ is nearly equal to 100%. For lower SNR ($$\leq$$ 20dB), $$P_d$$ increases for N greater than 400 samples. $$P_d$$ also increases with the increase of N and it achieves 100% value for N=1000. Thus, for small number of samples, the matched filter detector can work even at low SNR, and achieves 100% for 1000 samples.

Fig. 6. Simulation results for $$P_d$$ vs. N with variable SNR.
$P_d$ and $P_f$ were calculated by varying the SNR from -20dB to +20dB for several values of threshold factor. $N$ was chosen equal to 1000. Fig. 7 presents the $P_d$ as a function of SNR for several values of threshold factor. For fixed threshold factor, $P_d$ increases with SNR. As one can see, $P_d$ decreases when the threshold factor increases.

Fig. 7. Simulation results for $P_d$ vs. SNR with variable threshold.

Fig. 8 presents $P_f$ as a function of SNR for several values of threshold factor. For a high threshold factor ($Th_{\text{factor}} = 4$), $P_f$ decreases for a low SNR values (< -10dB); and when the threshold factor decreases, $P_f$ increases. For a fixed threshold factor and low SNR, $P_f$ is high. This figure also show the impact of the threshold on $P_f$ which decreases with the increase of threshold and SNR.

Fig. 8. Simulation results for $P_f$ vs. SNR with variable threshold.

These simulation results and others show that matched filter sensing technique can work under low SNR and with a small number of samples.

Table I presents a comparison between the proposed simulation and the other spectrum sensing techniques, energy detection and autocorrelation.

V. CONCLUSION

In this paper, we described the basic sensing methods and their simulation results were discussed. From the results of the comparison, we can conclude that each method has its strengths and weaknesses. Energy detection is easy to implement and does not require any information about PU signal; however it is not able to distinguish between signal and noise. It has also a high false alarm. Matched filter sensing requires a perfect knowledge of PU signal, which is not practical, but has a good performance under low SNR. Nevertheless, autocorrelation based sensing is robust against noise uncertainty. Therefore, choosing one of these three sensing techniques depends on the SNR level, noise uncertainty of the transmission channel, and available information about the PU signal. In addition, using a dynamic threshold gives better sensing performance than when using a static threshold.

REFERENCES


TABLE I. SPECTRUM SENSING TECHNIQUES COMPARISON

<table>
<thead>
<tr>
<th>Energy detection</th>
<th>Autocorrelation based sensing</th>
<th>Matched filter detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low complexity</td>
<td>High data processing</td>
<td>High complexity</td>
</tr>
<tr>
<td>Prior knowledge of PU signal is not required</td>
<td>Knowledge of statistical distribution of the autocorrelation function is required</td>
<td>Prior knowledge of PU signal is required</td>
</tr>
<tr>
<td>- Non-ability to distinguish between noise and signal after detection</td>
<td>- Ability to distinguish between PU signal and noise after detection</td>
<td>- High performance for low sample number</td>
</tr>
<tr>
<td>- Good performance under high SNR</td>
<td>- Robust against noise uncertainty</td>
<td>- Ability to perform under low SNR region</td>
</tr>
</tbody>
</table>

These simulation results and others show that matched filter sensing technique can work under low SNR and with a small number of samples.


