Chapter – 3

Improvement in Total Sensing Time of the Receiver

3.1 Introduction

In this Chapter, we have emphasized on the total sensing time of the adaptive sensing receiver (ASR) of the cognitive radio network. To minimize the total sensing time that is the time taken by the receiver to sense the spectrum, a potential modification has been made in the basic cognitive radio receiver architecture. The cognitive radio is a novel communication network, which is useful in utilizing the licensed spectrum by the unlicensed users when it is not being used by the licensed users. In order to reduce the sensing time of ASR, we have increased the number of antennas being used for ASR in the cognitive radio. The range of frequencies being utilized is increased to a large extent for various potential applications. The multitude of different wireless devices and technologies, the dramatic increases in the number of wireless subscribers, the advent of new applications, and the continuous demand for higher data rates are all reasons for the radio frequency spectrum becoming more and more crowded. This development calls for systems and devices that are aware of their surrounding radio environment, hence, facilitating flexible, efficient, and reliable operation and utilization of the available spectral resources. Wireless communication and radar systems must collect information about the radio spectrum in order to adapt their operation and behaviour to provide a better match to the prevailing conditions. Thus, spectrum sensing is becoming increasingly important to modern and future wireless communication and radar systems for identifying underutilized spectrum and characterizing interference, and consequently, achieving reliable and efficient operation [90, 91]. The licensed spectrum allocation method appears to have low spectrum utilization in many part of the frequency band. In order to utilize the inactive frequency bands, CR users must perform the spectrum sensing for the CR used frequency band frequently or periodically. The dedicated sensing receiver [91] in the CR plays an important role in sensing the spectrum. Recently, we are observing that the government is auctioning the spectrum usage for 3G applications. So, one must be very cautious in utilizing the spectrum. There are various
unused resources in frequency, time and space [87, 88] which are known as spectrum holes. CR has the capability in sensing and utilizing the unutilized spectrum in an unlicensed manner [9-11].

3.2 Proposed Adaptive Sensing Receiver Architecture

3.2.1 Proposed approach for improving performance

Cognitive radio along with dedicated sensing receiver is to distribute the work load and decision making. This combination will speed up sensing and make a reliable decision. Apart from these functionalities, continuously refine the decision making process while keeping the circuit complexity to a minimum. It has been observed that the sensing time is reduced to a great extent when we use an ASR along with the conventional receiver within the cognitive radio. The responsibility of sensing the spectrum is equally divided among both the receivers. There is a Look up Table (LUT) [92, 93] attached to the ASR which updates the range of spectrum to be sensed. There are two types of sensing algorithms along with ASR: i) Coarse sensing [1] which senses only those ranges which the cognitive radio is allowed to operate. These ranges include military, aerospace and many other ISM ranges. This reduces a lot of time in sensing. ii) Fine sensing [93] which senses the range of frequencies being specified after the coarse sensing is over. Opportunistic spectrum access by the secondary users is inherently dictated by the characteristics and operation of the primary users. The primary users have the privileged access to the frequency band for which they possess a license. Hence, the secondary users must guarantee their ability to share the spectrum while maintaining the interference caused to the primary users at an acceptable level. General treatments discussing the requirements and implementation issues of spectrum sensing may be found in [92-95]. A more practical opportunistic access concept relies on secondary users identifying frequency bands unused by the primary users and transmitting at those frequency bands until a primary user becomes active. Such a frequency band or channel is called a spectrum opportunity [94-96]. Spectrum opportunity is a local concept that may be defined as follows: A channel is an opportunity to a secondary transmitter A and secondary receiver B if they can communicate successfully over this channel while
limiting the interference to primary users below a prescribed level determined by the regulatory policy. A spectrum opportunity means that there are no primary receivers that would be interfered by the secondary transmitter A transmitting and no primary transmitters that would interfere the secondary receiver B from receiving in the same band at the same time.

The inherent requirement is that the secondary users must vacate the spectrum as quickly as possible when the primary user appears. Moreover, in order to guarantee low-interference operation of the primary users, the detection sensitivity of the cognitive radio users has to be very high. Note that some interference must be tolerated otherwise opportunistic access based on spectrum sensing is not possible. The total sensing time is reduced using a multi-resolution sensing technique shown in Fig. 3.1 wherein the total system bandwidth is first sensed using a coarse resolution. A fine resolution sensing is then performed over a small range of frequencies. This technique not only reduces the total number of blocks that must be sensed, it also allows the cognitive radio to avoid sensing the entire system bandwidth at the maximum resolution.

FIG. 3.1 TYPICAL COGNITIVE RECEIVER FOR TWO STAGE SENSING.
3.2.2. Coarse spectrum sensing

Coarse sensing depends on the information available in the LUT. The sensing receiver classifies the users as primary and secondary. We use spectrum matching detector (SMD) for detecting signals with low or negative SNR. As SMD has certain limitations we also use approximate SMD (ASMD) which can be implemented by discrete Fourier transform [57]. Coherent detectors are used when the PU (primary user) is known and ASMD is used when PU is unknown [96-97].

3.2.3. Fine spectrum sensing

After coarse sensing a list of candidate frequencies are given to the main receiver as shown in Fig.3.2. The main receiver performs fine sensing on a smaller set of prioritized signals. For fast scanning, ASR uses non coherent energy detection to complete coarse sensing before it proceeds to fine sensing. The most common approach in fine sensing is to perform Fast Fourier Transform (FFT). As FFTs are computationally intensive and with increase in the resolution the power consumption and the time taken for computations increases an adaptive FFT is used in which the number of FFTs vary with the operating conditions $B_{sys}$ [98-102]

![Diagram](image.png)

**FIG. 3.2. COARSE AND FINE FREQUENCY BINS[91]**
3.2.4 Adaptive sensing receiver model and its operational mechanism

As shown in Fig.3.1, this receiver works on the basic principle of bandpass sampling theorem. In this block diagram there are two different RF bandpass filters are placed successively to transform the incoming radio frequency signal to the baseband sampling. In this operational mechanism there are two types of sensors known as coarse sensor and fine sensors. The analog type sensors mostly supported for coarse sensing to find the potential candidature frequencies and also update the look up table as when the necessary information is available. Generally fine sensing will take place in the digital domain by the periodogram approach. The number of bins with the aid of the Fast Fourier Transform will conducive to compute the periodogram for the estimation of the unutilized bands.

![Diagram of ASR Model](image)

3.2.5 ASR along with main receiver

The ASR model which described in the earlier part must completely dedicated for the scanning the available spectrum in continuous manner. The main receiver along with ASR as shown in Fig.3.4 clearly indicates the different functionalities of each segment.
The main receiver supports the ASR whenever it is in idle state. In generally once the identified spectrum holes are handover by the ASR to the main receiver segment, it will do the fine sensing operational mode. When the potential unused bands or spectrum holes are identified, the main receiver is handover to the cognitive transmitter. The sole idea is to trace out the unused means by means of perfect coordination between main receiver and ASR segment.

**Fig. 3.4 MAIN RECEIVER ALONG WITH ASR HIGH LEVEL BLOCK DIAGRAM.**
3.3 The adaptive sensing receiver algorithm

The major objective of this algorithm is to reduce the overall sensing time and try to avoid the false detection alarms. In this specific algorithm, as mentioned above in Fig. 3.5, we initialize sensing function and simultaneously updating the lookup table (LUT). Apart from providing the user preference and geographical locations fed into the LUT and also scan the radio frequency spectrum continuously. These initial conditions help the cognitive radio to avoid known frequencies so that sensing time will be reduced. The cognitive radio updates the information regarding the channel and user status in the LUT on a continuous basis. This algorithm may be useful by allowing the receiver to demodulate the specific controlled channels. The central theme of this algorithm is simultaneously updating the number of candidate frequencies for cognitive radio operation and search for the suitable bands for future operation. The scanning the each frequency on the basis of figure of merit and this adaptive sensing receiver assigns weightage as 0, 0.25, 0.5, 0.75 and 1. “0” weightage means that associated frequencies
are prohibited for cognitive

radio operation. The unwanted frequency bands categorized as the non-candidates by using initial setup and scanning the radio frequency. This in turn will save the time and power for this unwanted frequency bands and as a next step this algorithm forced to move to the additional or next levels of sensing. The algorithm fully exploit the combined benefits of sensing at the different levels and also localize the decision making process very close to the desired sensing point. With full utilization of the dedicated receiver the better decision making process is feasible by making use of continuously sensing and adapt to the external environment without adding any system complexity. The faster scan will be feasible by prioritizing the historically used frequencies and as a next step wide range of sweeping the spectrum [102-105].

3.4. Analytical approach for finding the sensing time

In implementation, the overall system bandwidth $B_{sys}$ is divided into frequency bins. $B_{sys}$ is divided into coarse sensing bins $B_{crs}$ and fine sensing bins $B_{fin}$. $B_{crs}$ is a multiple integer of the $B_{fin}$.

$$B_{crs} = \alpha B_{fin} \quad \text{where} \quad \alpha = 1,2,3,4 \ldots$$

(3.1)

The resolution of the estimation is proportional to $N$. Hence the resolution increases as $N$ increases. For the sensing,

$$B_{fin} = NF_{res}$$

(3.2)

where $F_{res}$ is the resolution of sensing. In practical implementations, FFTs have widely used the split – radix algorithm. In this algorithm total number of real operations are $(4N \log_2 N - 6N + 8)[103]$. The total time to perform a discrete Fourier Transform (DFT) is given by:

$$T_{DFT} = \frac{1}{F_{DSP}} (4N \log_2 N - 6N + 8),$$

(3.3)
Where \( F_{DSP} \) is the DSP operating frequency. The total sensing time for coarse and fine sensing of the total bandwidth is given by
\[
T_{sys} = \frac{E_{SYS}}{E_{CRS}} T_{DFT}
\]  
(3.4)

Combining (3.1),(3.2) and (3.3) and assuming that in coarse mode, \( M \) receivers share the sensing load, we can write \( T_{crs} \) as:
\[
T_{crs} = \frac{E_{SYS}}{aMN_{crs} F_{res} F_{DSP}} \left[ 4N_{crs} \log_2(N_{crs}) - 6N_{crs} + 8 \right]
\]  
(3.5)

In fine mode, the total fine processing time is given by:
\[
T_{fin} = \alpha \cdot T_{DFT}
\]  
(3.6)

Combining (3.1), (3.3) and (3.6) is given by:
\[
T_{fin} = \frac{\alpha}{r_{DSP}} \left[ 4N \log_2(N_{fin}) - 6N_{fin} + 8 \right]
\]  
(3.7)

Combining (3.5) and (3.6), the total time \( T_{DFT,sys} \) to perform the FFT operation across coarse and fine sensing is given by:
\[
T_{sys} = \frac{E_{SYS}}{aMN_{crs} F_{res} F_{DSP}} \left[ 4N_{crs} \log_2(N_{crs}) - 6N_{crs} + 8 \right] + \frac{\alpha}{F_{DSP}} \left[ 4N \log_2(N_{fin}) - 6N_{fin} + 8 \right]
\]  
(3.8)

In order to compute the overall sensing time, we need to include the radio tuning time which is mostly dominated by PLL lock times. Here, we have to consider three locking times. \( T_{init} \) is the initial lock time, \( T_{PLL, crs} \) is the PLL lock time for coarse step and \( T_{PLL, fin} \) which is the PLL lock time for a fine step. Hence the total PLL sweep time \( T_{PLL, SYS} \) during the sensing operation is given by [103] :
\[
T_{PLL, SYS} = T_{init} + \alpha \beta T_{PLL, fin} + \beta T_{PLL, crs}, \quad \text{Where} \quad \beta = \frac{E_{SYS}}{E_{crs}}
\]  
(3.9)

Combining (3.8) and (3.9) the total sensing time \( T_{sys} \) is given by [104] :
\[
T_{sys}(DSR) = \frac{E_{SYS}}{aMN_{crs} F_{res} F_{DSP}} \left[ 4N_{crs} \log_2(N_{crs}) - 6N_{crs} + 8 \right] + \frac{\alpha}{F_{DSP}} \left[ 4N \log_2(N_{fin}) - 6N_{fin} + 8 \right] + T_{init} + \frac{\alpha \beta}{M} T_{PLL, fin} + \frac{\beta}{M} T_{PLL, crs}
\]  
(3.10)
3.5 Total Sensing Time for proposed ASR architecture:

In the proposed adaptive sensing architecture, this is based on the RF bandpass sampling receiver architecture. This architecture primarily based on the working principle of bandpass sampling theorem, which in turn depends on the interpolation technique. Compared to the dedicated sensing receiver, which in generally depends on the locking on the incoming signal frequency to the local oscillator frequency. This lock-in frequency will create latency in the sensing time that cumulatively affects the total sensing time of the detection process. In our proposed adaptive sensing receiver (ASR) approach it purely depends on the direct RF bandpass sampling receivers, where the need of the local oscillator is not required. This will give the substantial time saving in the computation of the overall sensing time. Due to this reason we will discard the initial lock-in time $T_{init}$, and also PLL delays due to coarse and fine sensing timings. In our architecture total sensing time will depends only on the total coarse and fine sensing times only. In this way, our proposed ASR architecture will reduce the sensing time based on the formulae given below for computational and simulation purpose.

$$T_{SYS(ASR)} = \frac{B_{SYS}}{aMN_{crs}f_{ddp}f_{DSP}} \left[ 4 \log_2(N_{crs} - 6N_{crs} + 8) \right] + \frac{N}{f_{DSP}} \left[ 4N \log_2(N_{fin} + 6N_{fin} + 8) \right]$$

(3.11)

In the above equation $M$ is the number of antennas used for reduction of the overall sensing time as indicated in Fig. 3.6.

3.6 Simulation Results

Table 3.1: Simulation Parameters

<table>
<thead>
<tr>
<th>System frequency of operation($B_{SYS}$)</th>
<th>0-10 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{crs}$</td>
<td>100MHz</td>
</tr>
<tr>
<td>$B_{fin}$</td>
<td>10MHz</td>
</tr>
<tr>
<td>DSP frequency($f_{DSP}$)</td>
<td>100MHz</td>
</tr>
<tr>
<td>Sensing resolution($f_{res}$)</td>
<td>10KHz</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>VCO control voltage</td>
<td>1V</td>
</tr>
<tr>
<td>PLL phase jitter (Max)</td>
<td>1.0deg rms</td>
</tr>
<tr>
<td>Initial lock time</td>
<td>1.1ms</td>
</tr>
<tr>
<td>For a single coarse channel jump of 100 MHz, the coarse lock time ($T_{PLL_crs}$)</td>
<td>0.6ms per channel</td>
</tr>
<tr>
<td>For a single fine step of 10MHz,$T_{PLL_fin}$</td>
<td>0.35ms</td>
</tr>
<tr>
<td>Number of fine channel scan between frames during normal CR operation</td>
<td>100</td>
</tr>
<tr>
<td>% yield of candidate channels after coarse sensing-$\alpha$</td>
<td>40%</td>
</tr>
<tr>
<td>% coarse bins known as bad channels</td>
<td>30%</td>
</tr>
<tr>
<td>FFT points for coarse mode($N_{crs}$)</td>
<td>128</td>
</tr>
<tr>
<td>FFT points for fine mode($N_{fin}$)</td>
<td>1024</td>
</tr>
<tr>
<td>Number of antennas</td>
<td>1-4</td>
</tr>
</tbody>
</table>

**FIG. 3.6 THE SENSING TIME, $T_{sys}$ VERSUS NUMBER OF ANTENNAS, $M (B_{sys}=1\ \text{GHz}, F_{size}=10$ $\text{KHZ}, N=64, \alpha = 10)$.**

Another important consideration for the cognitive radios is the sensing policy that includes decisions such as when and how long to sense, and which frequency band to
sense. In order to maximize performance, the sensing policies should be coordinated among the secondary users. Simultaneous transmission and sensing on a given frequency is not possible in general. Hence, sensing and transmission have to be done in an alternating manner. Moreover, the sensing periods must be synchronized among the cognitive radios. Ideally a cognitive radio user wants to minimize the time required for identifying spectral opportunities in order to maximize the time available for transmission. Different primary systems impose different constraints for sensing. The total sensing time while considering a ASR along with the other receiver is found out to be 71ms as shown in Fig. 3.7 (a). So, cannot reduced this time so that the sensing operation takes place quickly which led to think about the possible ways in reducing this time. The total sensing time can be calculated by using the expression as stated in Equation (3.10). The number of FFT points required to compute the periodogram is linearity increases with number of FFT points as shown in Fig. 3.7 (b) for sensing time in milliseconds. The parameters being used in the Equation (3.1) and (3.2) have been tabulated. The values of alpha and beta are calculated from below Equations (3.11) and (3.12) from [104].

\[ \beta = \left( \frac{B_{SYS}}{B_{cts}} \right) = \frac{10 \text{GHz}}{100 \text{MHz}} = 100 \]  

(3.11)

\[ \alpha = \left( \frac{B_{cts}}{B_{fs}} \right) = \frac{100 \text{MHz}}{10 \text{MHz}} = 10 \]  

(3.12)

The values of \( \alpha \) and \( \beta \) being considered are 10 and 28, respectively considering that 70 out of the 100 channels are good. The remaining 30 channels may be in the avoidance zone. So, \( \beta \) which is the number of coarse bins is taken to be 40% of the available channels. So, \( \beta \) turns out to be 28. Now taking into account the other unknown, \( \alpha \) is calculated as 10 as it the number of fine bins available. Thus we will be using these values in our calculations. We are concerned to reduce the total sensing time. As we can see from the above formula that the total sensing time is inversely proportional to the number of antennas used for sensing. So, we use an array of smart antennas say from 100 to 500 and substituting all the parameters in the Equation (3.11) gives us a plot between the total sensing time and the number of antennas for a given frequency of
operation as shown in Fig. 3.8. We observe from the graph above that the total sensing time \((t_{sys})\) is reduced to a great extent as we keep on increasing the number of antennas.

(a)

FIG. 3.7 (A) SENSING TIME, \(T\) VERSUS NUMBER OF ANTENNAS, \(M\) (DIFFERENT VALUES OF \(\alpha\), \(B_{sys} = 1\) GHZ, \(F_{RES} = 10\) KHZ, \(N = 64\)), AND (B) SENSING TIME VERSUS NUMBER OF FFT POINTS.
This graph proves the inverse relationship between the total sensing time and the number of antennas. Before this the sensing time calculated was 71 ms and now with the help of smart antennas this is reduced to nearly 1.5 ms. We started with frequency of 10 GHz and kept on increasing till 100 GHz. With the increase in frequency there is an increase in the total sensing time, however, as we keep on increasing the number of antennas along with the frequency, can reduce the total sensing time. Let us look at the plot by the values. If we fix the frequency as 10 GHz and the number of antennas as 100 we get $t_{sys}$ as 2.9562 ms. Now at the same frequency if we increase the number of antennas to 200, we get $t_{sys}$ as 2.0281 ms and finally at 500 antennas, we get $t_{sys}$ as 1.4712 ms as shown in Fig 3.9. Even though, there is an increase in $t_{sys}$ with an increase in frequency, we can reduce $t_{sys}$ with an increase in the number of antennas at such high frequencies.
FIG. 3.9 TOTAL SENSING TIME (VERSUS) NUMBER OF ANTENNAS (FOR DIFFERENT SYSTEM BANDWIDTHS)

Table 3.2 Simulated improvements over base receiver versus proposed DSR architecture.

<table>
<thead>
<tr>
<th>Event of operation</th>
<th>Cognitive Receiver without ASR</th>
<th>ASR Architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total sensing time before initial CR operation</td>
<td>755.2 ms</td>
<td>71 ms</td>
</tr>
</tbody>
</table>

3.7 Results and Conclusions

With the preceding analysis, the total sensing time, number of antennas and the frequency range provide an interesting idea of the reduction in $t_{sys}$ which is achieved with a proper matching between the operating range of frequency and the number of antennas used. The main concern in increasing the number of antennas is the cost that
they may incur and other area of concern is the power consumption required for these antennas. The total time to perform the parallel, multi-resolution spectrum sensing if also calculated and it is seen that the method followed in this paper describes the content more practically. Further work is being concentrated upon the total mean detection time in which detection and false alarm probability will also be considered while calculating sensing time. There are multiple ways to improve the detection sensitivity of a cognitive radio network. The sensitivity of the cognitive radios may be improved by enhancing the cognitive radio’s RF front-end sensitivity, designing and employing powerful signal processing algorithms well-suited for the task, as well as by exploiting spatial diversity through collaborative sensing among multiple cognitive radios.