Theoretical Specification of a Spectrum Sensing Receiver for Cognitive Radio

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Abstract—This paper presents the theoretical specification of Spectrum Sensing Receiver used for Cognitive Radios. Its system level design is intended to comply with IEEE 802.22, IEEE 802.16 (Wimax) and LTE standards altogether. The operation frequency band is very wide, from 50MHz to 3.8GHz. Calculated specifications include noise figure, compression point, third order intercept point, sensitivity and signal-to-noise ratio (SNR). Results show the most challenging requirement is the linearity in the entire frequency band. In addition, noise figure become a limitation for detection of weak signals.

Keywords - Cognitive radio, RF receiver design, spectrum sensing, noise figure, linearity, sensitivity, signal-to-noise ratio

I. INTRODUCTION

Since radio spectrum is a finite resource, the increasing spectrum utilization [1] and its fixed band allocation will lead to a spectrum scarcity. After spectrum occupation surveys, it was observed that certain band of the spectrum are severely underutilized [2,3]. The Cognitive Radio concept appears as solution for spectrum underutilization, allowing secondary users to use the vacant channels while primary uses are not communicating [4]. However, Cognitive Radios need a trustful and fast Spectrum Sensing (SS) operation to find vacant channels.

Every design project starts with the specifications, [5] and [6] already presented the calculation methodology for IEEE 802.16 (Wimax) and IEEE 802.22 receivers, respectively. But these specifications do not comply with a SS receiver. Main differences are in signal-to-noise ratio (SNR) and sensitivity calculation, because in SS receiver the objective is to detect signals, not to decode them. SS operation does reduce the SNR requirement, and also requires higher sensitivity from the receiver. Also, if SS receiver is multi standard and wideband, its linearity requirements are very high.

In this work a theoretical calculation of specifications for a SS receiver is presented, including calculation of receiver signal-to-noise ratio, sensitivity, noise figure, compression point and third order intercept point.

The paper is organized as follows. In Section II, signal-to-noise ratio calculation is presented. Section III presents considerations about receiver’s sensitivity and noise figure, and also related calculations. The methodology used to calculate circuit linearity is presented in Section IV. Section V concludes the paper, with final comments and future works.

II. SIGNAL-TO-NOISE RATIO

The signal-to-noise ratio (SNR) desired for a spectrum sensing receiver is determined by detection theory [7]. The detection is based on statistic test (T), which is compared with a detection threshold. If the statistic test is larger than the threshold, the channel is classified as occupied and if the statistic test is equal or smaller than the threshold, the channel is classified as vacant. The statistic test for energy sensing technique is,

$$T = \frac{1}{M} \sum_{n=1}^{M} y(n) \cdot y^*(n),$$

where $M$ is the number of samples and is $y(n)$ the signal [8].

The probability of detection calculation is based on the selection of threshold and false alarm probability. False alarm probability is defined as the probability of wrongly classify a vacant channel as occupied. In addition, a small value is set to these probability due to the disastrous consequences that a false alarm can cause [7]. Since consequences of false alarm are less serious for radio communications than for a radar, the spectrum sensing can operate with a larger false alarm probability. The threshold chosen has to maximize the detection probability for a fixed value of false alarm probability. In [8] the threshold formula is,

$$y = P_N \left( 1 + \frac{Q^{-1}(P_{FA})}{\sqrt{M}} \right),$$

where $P_N$ is noise power, $Q(x)$ is the right-tail probability function and $P_{FA}$ is the false alarm probability, which is the probability of exceeding a given value. Also, in [8] the detection probability is given by,

$$P_D = 1 - Q\left( \frac{\sqrt{M}}{P_S + P_N} ; P_S + P_N - y \right),$$

where $P_S$ is signal power and $P_D$ is detection probability. It is well know that,

$$\text{SNR} = \frac{P_S}{P_N},$$

Using 4, it is possible to rewrite 3 as,
\[ P_D = 1 - Q\left(\sqrt{\frac{M}{N}} - \sqrt{\frac{Q^{-1}P_{fa}}{SNR + 1}}\right). \]  

(5)

In [8] the requirement of false alarm probability is below 10% and detection probability is above 90%. So, equation 5 is plotted in Fig. 1 using \( P_{fa} = 0.1 \) and a number of samples of 100, 1000 and 10000. The SNR suffer a high variation for different number of samples. Detection of a higher number of samples allow lower SNR values, but will increase the sensing time. Because of that, it is preferable to work with a lower number of samples. For further calculation a SNR of -10dB will be assumed, which is achieved for a number of samples close to 1000.

![Fig. 1: Plots of SNR x PD for different number of samples.](image)

**III. SENSITIVITY AND NOISE FIGURE**

Sensitivity is the smallest signal power that a receiver can detect with "acceptable quality", which means a sufficient SNR [9]. The sensitivity equation is given by

\[ P_{\text{min}} = P_{BS} + NF + 10\log(B) + SNR_{\text{min}} + M, \]

(6)

where \( P_{\text{min}} \) is the sensitivity in dB, \( P_{BS} \) is the source resistance noise power in dBm/Hz, \( NF \) is the noise figure in dB, \( B \) is the bandwidth in Hz, \( SNR_{\text{min}} \) is the minimum signal-to-noise ratio in dB and \( M \) is the implementation margin in dB. If the receiver is matched to the RF antenna, then

\[ P_{BS,dBm/Hz} = kT, \]

(7)

where \( k \) is the Boltzmann constant and \( T \) is the environment temperature.

In [8] sensitivity for spectrum sensing was defined as -114dBm for television signals and wireless microphones and -116dBm for IEEE 802.22 signal. However, there are no definition of sensitivity for spectrum sensing in Wimax [10] and LTE [11] standards. In both cases, the path loss equation and the minimum transmitter output are used to define the maximum distance that the spectrum sensing can detect a signal and the sensitivity for that distance. The path loss equation \([8]\) is,

\[ P_{RX} = P_{TX} - 20\log\left(\frac{\pi f_c}{c}\right) - n \cdot 10\log\left(d_0\right), \]

(8)

where \( P_{RX} \) is the signal power received at the receiver in dB, \( P_{TX} \) is the signal power transmitted by the transmitter in dB, \( f_c \) is the carrier frequency in Hz, \( n \) is the path loss exponent, \( d_0 \) is the reference distance in meters and \( d \) is the distance between transmitter and receiver in meters \([12]\). Using the worst situation for the previous parameters and the path loss exponent for free space, the signal power received for a chosen distance it is calculated.

Fig. 2 shows the receiver input power for distances below 1km. In order to detect a Wimax or LTE signal 1km away from the receiver, a sensitivity of -130.81dBm and -144dBm, respectively, is required. Both sensitivities are very hard to achieve for energy sensing, especially LTE sensitivity. Hence, for further calculation, a sensitivity of -125dBm will be used, which allows the detection of Wimax signals from transmitter's 512m away and LTE signals from transmitter's 111m away.

Equation 6 is plotted in Fig. 3, for the desired sensitivity, at 300K and an implementation margin of 2dB. Despite the channel bandwidth of the signals to be detected varying from 100kHz to 20MHz the noise figure has to be considered at the worst case, which is 3.83dB at 20MHz.

**IV. LINEARITY**

The linearity of a circuit can be measured by its 1dB compression point and the third order intercept point. The 1dB compression point is the input signal power that causes the gain to drop by 1 dB due to circuit nonlinearities. Third order intercept point measures the nonlinearity due to intermodulation products of two interfering signals accompanying the desired signal [9].

Signals from the standards covered in this work \([8,10,11]\) are OFDM (Orthogonal Frequency Division Multiplexing) which uses quadrature amplitude modulation (QAM). OFDM systems exhibit large amplitude variation due to subcarriers interaction [9]. Since this amplitude variations can make the circuit compress, severe linearity requirements are imposed.

In order to calculate the receiver 1 dB compression point is considered the maximum receiver input power and peak-to-average ratio (PAR). The equation to calculate the 1dB compression point is,

\[ CP = P_{\text{PAR}} + PAR, \]

(9)

where \( CP \) is the 1dB compression point in dBm and \( P_{\text{PAR}} \) is the maximum signal power that the receiver can decode in dBm. And IIP3 is usually 9.6dB larger than 1dB compression point [9].

Receiver maximum input power are -41dBm [6] for IEEE 802.22, -30dBm [10] for Wimax and -25dBm [11] for LTE. PAR is given by maximum value of the squared signal divided by average value of the squared signal,

\[ PAR = \frac{\text{Max}[x^2(t)]}{x^2(t)}. \]

(10)
However, the value given by equation 10 is the maximum PAR and the probability of its occurrence is close to zero [13], [9]. In [13] is proven that values of PAR for a large number of subcarriers are concentrated at the interval,

$$2\ln(N) + \ln(\ln(N)) \leq \text{PAR} \leq 2\ln(N)$$

where $N$ is the number of subcarriers. In Table I the results of 1dB compression point and IIP3 are summarized. Since LTE results are the worst case, it will be used as the receiver linearity specification.

**Table I: PAR, 1dB Compression Point and IIP3 Results.**

<table>
<thead>
<tr>
<th>Number of subcarriers</th>
<th>PARMAX (dB)</th>
<th>Compression point (dBm)</th>
<th>IIP3 (dBm)</th>
</tr>
</thead>
</table>

![Sensitivity for different distances between transmitter and receiver.](image)

**Fig. 2:** Sensitivity for different distances between transmitter and receiver.

![Noise Figure variation due to channel bandwidth.](image)

**Fig. 3:** Noise Figure variation due to channel bandwidth.

V. CONCLUSION

This paper presented a theoretical calculation of a spectrum sensing receiver specifications. As shown in Table II, the spectrum sensing specifications for multiple standards are more challenging than specifications for usual receivers due its multiple standard approach and the lower sensitivity requirement.

Analysing the results presented in Table II, linearity seems to be the main challenge in a future circuit design due to its high value and the wide frequency band chosen. In addition, the need for further increase of channel bandwidth, as well as decrease of circuit sensitivity can turn noise figure in a constrain for the receiver. This work next step is to divide the specifications between the blocks that compose the receiver for SS operation.

**Table II: Overall Specifications.**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>SNR (dB)</td>
<td>-10</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Sensitivity (dBm)</td>
<td>-125</td>
<td>-91</td>
<td>-92</td>
</tr>
<tr>
<td>NF (dB)</td>
<td>3.83 @20MHz</td>
<td>0 @20MHz</td>
<td>10 @6MHz</td>
</tr>
<tr>
<td>1dB CP (dBm)</td>
<td>-10.82</td>
<td>-18</td>
<td>-29.8</td>
</tr>
<tr>
<td>IIP3 (dBm)</td>
<td>-1.22</td>
<td>-8</td>
<td>-19.8</td>
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REFERENCES