System Design Considerations for an Analog Frontend Receiver in Cognitive Radio Applications

Sandro Ferreira\textsuperscript{1}, Filipe Dias Baumgratz\textsuperscript{2}, Sergio Bampi\textsuperscript{3}

\textsuperscript{1}PGMICRO, UFRGS
Porto Alegre, RS, Brazil
\textsuperscript{2}fdbaumgratz@inf.ufrgs.br
\textsuperscript{3}bampi@inf.ufrgs.br

Abstract— This article presents a brief overview of the Cognitive Radio technology and applications, focusing in the Standard IEEE 802.22 as well as in an extension of the frequency band application to the range of 54 MHz to 4 GHz. A direct conversion strategy is proposed and the receiver scenery is taken in account in order to present standard targets for the main receiver specifications such as noise figure, sensitivity and linearity.

Keywords— Cognitive Radio, IEEE802.22, direct conversion, receiver architecture, receiver linearity.

I. INTRODUCTION

The successful operation of unlicensed bands such as the industrial, scientific and medical radio bands (ISM) and the advances in technology led regulatory bodies to open licensed bands for unlicensed use [1]. Taking into account that some licensed bands such as TV bands are significantly underused, the Federal Communications Commission (FCC) decided to open licensed TV bands for unlicensed broadband operations [2] [3], helping to improve broadband access in rural areas.

To use this recently available frequency band, IEEE created the Working Group IEEE 802.22 Wireless Regional Area Networks (WRAN) focusing on the development of specifications for a cognitive radio architecture to be adopted for wireless regional area network applications using TV unused frequencies (white spaces). This cognitive radio concept implies that the network have to protect incumbent TV and wireless microphone users.

In order to be implemented, this technology requires the adoption of wideband or multiband receivers. Wideband receivers use simpler architectures while multiband receivers permit the optimization of radio performance parameters such as noise figure, linearity, gain and impedance matching, although usually requiring complex matching networks. This improved specifications are a consequence of the reduced frequency band during operation that reduces also the number of interferers that have to be considered in each band. Nevertheless, a multiband approach might reduce receiver flexibility.

The main IEEE 802.22 characteristics were defined by the Standard in 2011 [4] and are listed in Table I.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specification</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>54 ~ 862 MHz</td>
<td></td>
</tr>
<tr>
<td>Channel Bandwidth</td>
<td>6, 7, or 8 MHz</td>
<td></td>
</tr>
<tr>
<td>Data rate</td>
<td>4.54 to 22.69 Mbps</td>
<td>For QPSK 1/2 and 64QAM 5/6</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK, 16QAM, 64QAM</td>
<td></td>
</tr>
<tr>
<td>Multiple Access</td>
<td>OFDMA with 2048 FFT Size</td>
<td></td>
</tr>
<tr>
<td>Cell Coverage</td>
<td>17 to 33 km</td>
<td></td>
</tr>
</tbody>
</table>

This paper presents initial considerations for an extension of IEEE 802.22 Standard to the frequency range of 54 MHz to 4 GHz focusing in the increased linearity issues for the analog frontend receiver. It is structured as follows. Section II presents the main receiver design considerations. Section III presents the receiver scenery for this application while Section IV presents some preliminary conclusions.

II. RECEIVER DESIGN CONSIDERATIONS

For a top-level design of the receiver, some requirements have to be considered from the very beginning. This section concentrates on explaining basic parameters involved in the top level design, namely: noise figure, sensitivity, maximum input signal, and dynamic range.

A. Noise Figure and Noise Factor

Noise Factor is defined as the ratio between the signal-to-noise ratio at the input and the signal-to-noise ratio at the output. It characterizes how much noise was inserted by a specific block or system (Eq. 1).

\[ F = \frac{SNR_i}{SNR_o} \]

(Eq. 1)
Noise Figure is the Noise Factor expressed in decibels (dB). It defines the sensitivity, the lowest level of the dynamic range (DR) of receivers.

B. Sensitivity

Sensitivity of an RF receiver is defined as the minimum detectable signal (MDS) with acceptable signal-to-noise ratio [5]. Since $SNR_{o}$ can be given by the ratio between input power ($P_{sig}$) and input noise given by $kTB$, where $k$ is the Boltzmann constant, $T$ is the temperature in Kelvin and $B$ is the bandwidth. Noise Factor can also be expressed in terms of these parameters and Eq. 1 can be presented as Eq. 2.

$$F = \frac{P_{sig}/kTB}{SNR_{o}}$$

(2)

Sensitivity is given by Eq. 3 by rearranging Eq. 2. The minimum $SNR_{o}$ is determined by the error vector modulation (EVM) or the bit error rate (BER) required by the considered modulation.

$$S = P_{sig} = F \cdot SNR_{o,min} \cdot kTB$$

(3)

Considering a channel of 6 MHz (Table I), the signal-to-noise ratio necessary for the modulation types as proposed by the standard is presented in Table II for a BER performance of $2 \times 10^{-4}$ [4].

<table>
<thead>
<tr>
<th>Modulation - FEC rate</th>
<th>SNR for AWGN channel (dB)</th>
<th>Multipath channel (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDMA</td>
<td>1.2</td>
<td>5</td>
</tr>
<tr>
<td>QPSK, rate:1/2</td>
<td>4.3</td>
<td>8.1</td>
</tr>
<tr>
<td>64 QAM, rate:5/6</td>
<td>20.9</td>
<td>40.4</td>
</tr>
</tbody>
</table>

The more stringent requirement for the SNR is provided by the standard and it is equal to 40.4 dB for 64QAM with 5/6 rate in a multipath channel.

To determine the system sensitivity, noise figure is proposed by the IEEE 802.22 standard as 3 dB for the base station (BS) and 6 dB for the consumer premise equipment (CPE).

Sensitivity, defined by equation 3, should include receiver and interference margins ($Mrx$ and $M_{interf}$) as well as a safety margin for the decoder implementation, resulting in eq. 4.

$$S = noise + NF + SNR_{o} + M_{rx} + M_{interf} + M_{d}$$

(4)

Considering the SNR necessary for the detection of a signal of 6 MHz bandwidth given by Table II, the sensitivity of the system is -91.0 dBm for CDMA, -87.7 dBm for QPSK with 1/2 FEC rate and -55.2 dBm for 64-QAM with 5/6 FEC rate in a multipath channel.

C. Maximum Input Signal and Dynamic Range

The maximum input signal that can be accepted by a system is limited by the system linearity requirement. The difference between the maximum input signal and the MDS is defined as dynamic range (DR). The maximum input signal is also required by the analog-to-digital converter specifications since it has to accommodate every signal inside the analysed band without saturation.

As proposed by the standard, the maximum input signal that should be accepted in tolerance to receiver overload is -8 dBm [4].

D. Linearity

Linearity is usually expressed by the compression point ($P_{1dB}$) and by the third order intercept point (IIP3).

$IIP3$ is defined as the point where the power level at the output is compressed by 1dB. $IIP3$ can be calculated as 10 dB bigger than compression point and is a measure of the intermodulation products originated by the system nonlinearity.

To calculate the compression point for the OFDM using QAM modulation, an Input Back-Off of 12 dB is recommended. Considering this back-off which is recommended in order to accommodate the OFDM envelope that is defined by its Peak to Average (Power) Ratio (PAPR), the compression point is defined by Eq. 5 [10].

$$P_{1dB} = P_{in_{max}} + PAPR$$

(5)

Considering that the maximum input power proposed by the standard is about -41.8 dBm, it results in a compression point of -29.8 dBm with a consequent IIP3 of -19.8 dBm [10].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (dBm)</td>
<td>-91.0</td>
<td>CDMA</td>
</tr>
<tr>
<td></td>
<td>-87.7</td>
<td>QPSK:1/2 FEC</td>
</tr>
<tr>
<td></td>
<td>-55.2</td>
<td>64-QAM: 5/6 FEC</td>
</tr>
<tr>
<td>Noise Figure (dB)</td>
<td>6</td>
<td>For CPE users</td>
</tr>
<tr>
<td>Maximum Input Power (dBm)</td>
<td>-8</td>
<td>To be perceived at the ADC to accommodate interferers.</td>
</tr>
<tr>
<td>$P_{1dB}$ (dBm)</td>
<td>-29.8</td>
<td></td>
</tr>
<tr>
<td>$IIP3$ (dBm)</td>
<td>-19.8</td>
<td></td>
</tr>
</tbody>
</table>
III. RECEIVER SCENERY

In the frequency range considered in this design, from 54 MHz to 4 GHz, many commercial standards are present and should be considered as interferers or as incumbents as proposed by IEEE 802.22. Table IV presents the main incumbents in this frequency range.

Since the designed system have to cope with this scenery, maximum output power emissions to be received by the system antenna have to be considered as part of the interferers and may severely impact selectivity. Fig. 1 presents the estimated power to be received by the system after a short distance considering maximum power emissions for each one of the standards in Table IV.

**TABLE IV**

<table>
<thead>
<tr>
<th>Standard</th>
<th>Frequency Range (MHz)</th>
<th>BW(MHz)</th>
<th>Data rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.22 [4]</td>
<td>54 - 862</td>
<td>6, 7, 8</td>
<td>22.69</td>
</tr>
<tr>
<td>EDGE [6]</td>
<td>380 - 1900</td>
<td>0.2</td>
<td>0.06</td>
</tr>
<tr>
<td>WCDMA [6]</td>
<td>800 - 2600</td>
<td>5</td>
<td>14.4</td>
</tr>
<tr>
<td>LTE [7]</td>
<td>800 - 2600</td>
<td>20</td>
<td>173/86</td>
</tr>
<tr>
<td>IEEE 802.11 [8]</td>
<td>2400 - 2483.5</td>
<td>22</td>
<td>54</td>
</tr>
<tr>
<td>IEEE 802.16 [7]</td>
<td>2300 -3500</td>
<td>10, 20</td>
<td>21</td>
</tr>
</tbody>
</table>

Fig 1: Main interferers in the receiver scenery.

Linearity of the system can also be calculated taking into account the intermodulation ($P_{IM}$) caused by interferers or blockers ($P_{bl}$) in the adjacent channel. In this sense, out-of-band IP3 can be calculated by Eq. 6 [5].

$$IIP3 = P_{bl} + 1/2 (P_{bl} - P_{IM,i})$$

where, $P_{IM}$ is the tolerated intermodulation product and have to be smaller than the system sensitivity.

The effect of wideband signals is not taken into account in Eq. 6, consequently a factor of 4.5 dB have to be added to the blocker if it covers the entire proposed bandwidth as presented in literature [11].

IIP3 calculated with the blockers presented in Fig. 1 using sensitivity obtained in Table III can get to values as high as 52dBm for GSM when QPSK demodulation is considered. These values are prohibitive for CMOS implementations.

To be able to accept these strong interferers some alternatives have to be adopted such as to filter blockers in the rf section before they enter into the system or to only operate in alternate channels, leaving adjacent channels which are subjected to intermodulation products unoccupied.

Rf block filters are not adequate to cognitive radio applications since they limit the flexibility of the system, consequently the better approach is to avoid adjacent channels or intermodulation product spots. In this sense, the cognitive radio structure, presented by the spectrum sensing facilities proposed by the standard, can help in this intermodulation-free spot decision.

IV. CONCLUSIONS

This paper presented a brief overview of the cognitive radio standard IEEE 802.22 and a frequency band extension is proposed. The new receiver scenery is presented and its challenging linearity requirements are briefly discussed. Linearity as well as sensitivity and noise figure are the main requirements for the receiver top level design and its preliminary results are presented.

**REFERENCES**


