RF Sampling
Software Defined Radio for HF Band
Outline

- Introduction
- Sensitivity (NF) of SDR
- NF analysis for ADC
- Analysis of bit-length for DSP
- Analysis and design for front-end
- Conclusion
- Q&A
What is an ideal SDR architecture?

Depends on …

• receiving frequency
• receiving band width
Introduction

Current architecture of SDR is ...

Progressive and realistic architecture of SDR is ...

RF amplifiers are needed for keeping the NF.
We propose

a realistic SDR for HF band with very high sensitivity & IPs.

- no Analog Mixer (no image receptions)
- no Analog Synthesizer (no reciprocal mixing)
- no Analog AGC Circuits (no target reduction)
Introduction

How to establish the noise figure and design the appropriate RF amplifier...

- RF in
- LPF
- RF Amp
- A/D Conv.
- A/D
- D.S.P (DSP, FPGAs, GPP, ...)
- Data out
- Front-end
- ADC
- D.S.P

NF
NF
Quantization Error & Bit length
### Specification goal for SDR

<table>
<thead>
<tr>
<th></th>
<th>High sensitivity mode</th>
<th>Low distortion mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity (NF)</strong></td>
<td>NF : 8dB</td>
<td>NF : 14dB</td>
</tr>
<tr>
<td><strong>IPs (IP3in &amp; IP2in)</strong></td>
<td>IP3in : +20dBm</td>
<td>IP3in : +30dBm</td>
</tr>
<tr>
<td></td>
<td>IP2in : +60dBm</td>
<td>IP2in : +70dBm</td>
</tr>
</tbody>
</table>
How to establish the NF of ADC?

Example of ADC characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution [bits]</td>
<td>16 [bits]</td>
</tr>
<tr>
<td>Full-scale input swing voltage [V p-p]</td>
<td>2.75 [V p-p]</td>
</tr>
<tr>
<td>Sampling frequency [MHz]</td>
<td>100 [MHz]</td>
</tr>
<tr>
<td>Signal to quantization noise ratio S/N [dB]</td>
<td>81.1 [dB]</td>
</tr>
</tbody>
</table>

Amount of noise in ADC output [dBFS]

\[ = - \frac{S}{N} = -81.1 \text{[dBFS]} \quad (1) \]
Amount of noise in 1Hz BW of ADC can be described as…

\[
\text{Amount of noise in 1Hz BW of ADC output [dBFS]} = \text{Amount of noise in ADC output [dBFS]} - \text{Correction factor for 1Hz BW [dB]} \quad (2)
\]

Correction factor for 1Hz BW can be described as…

\[
\text{Correction factor for 1Hz Bandwidth [dB]} = 10\log(\text{Nyquist bandwidth} / 1\text{Hz bandwidth}) = 10\log(5e7) = 77.0 [\text{dB}] \quad (3)
\]

Amount of noise in 1Hz BW of ADC

\[
= -81.1 [\text{dBFS]} - 77 [\text{dB}] = -158.1 [\text{dBFS/Hz}] \quad (4)
\]
NF Analysis for ADC

Convert to the RF level:

\[
\text{full-scale voltage} = 2.75[Vp - p] = 0[dBFS] = 12.8[dBm] \quad (5)
\]

By using equation (4), (5)

noise in 1Hz BW of ADC output converts to the RF level:

\[
\text{noise in 1Hz BW of ADC output} = 12.8[dBm] - 158.1[dB] = -145.3[dBm] \quad (6)
\]

\[
\text{thermal noise in 1Hz BW} = 10\log(kT)[dBm] = 10\log((1.38e-23)(2.98e2)) = 10\log(4.11e-18) = 173.9[dBm] \quad (8)
\]

Where \( k = \) Boltzmann's constant, 1.38e-23
\( T = \) absolute temperature, K (298 K)
NF of ADC is designated as:

\[ \text{NF of ADC} = \text{ADC noise component in 1Hz BW} - \text{thermal noise in 1Hz BW} \]

\[ = -145.3[\text{dBm}] - (-173.9[\text{dBm}]) = 28.6[\text{dB}] \quad (9) \]

From equation (9),
NF of ADC can be assumed to be 28.6dB.
Analysis of the bit length for DSP

Process of Digital Signal Processing

Analog signal → ADC (NF=28.6[dB], Gain=1) → Digital Signal Processing (Gain=1)

Principal flow diagram of digital signal processing

ADC Output → CIC Decimation Filter → CIC Compensation Filter → FIR Filter

Decimation Filter → FIR BPF
Analysis of the bit length for DSP ②

Analysis of noise in the digital filter.

In-band noise of the filter

\[ = \text{inband noise of ADC output} + \text{quantization noise of itself} \quad (10) \]

Out-band noise of the filter

\[ = \text{outband quantization noise of it} \quad (11) \]

Amount of noise in the filter output

\[ = \text{inband noise of the filter} + \text{outband noise of the filter} \quad (12) \]
Analysis of the bit length for DSP

NF calculation of 16bit decimation filter and 16bit FIR filter

Decimation filters bit length: 16bit
FIR filters bit length: 16bit

NF (ADC+DSP)
NF (ADC Only)
Analysis of the bit length for DSP

Calculation of the good length bit for **decimation filters**

Decimation filters bit length: 16bit
FIR filters bit length: 32bit

Decimation filters bit length: 22bit
FIR filters bit length: 32bit
Calculation of the good length bit for **FIR filters**

Decimation filters bit length: 32bit
FIR filters bit length: 22bit

<table>
<thead>
<tr>
<th>BandWidth of FIR Filter [kHz]</th>
<th>NF (ADC+DSP)</th>
<th>NF (ADC Only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15</td>
<td>60</td>
<td>57.5</td>
</tr>
<tr>
<td>0.3</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>0.6</td>
<td>52.5</td>
<td>52.5</td>
</tr>
<tr>
<td>1.5</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>2.4</td>
<td>47.5</td>
<td>47.5</td>
</tr>
<tr>
<td>3.2</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>42.5</td>
<td>42.5</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>37.5</td>
<td>37.5</td>
</tr>
<tr>
<td>30</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>50</td>
<td>32.5</td>
<td>32.5</td>
</tr>
<tr>
<td>120</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>200</td>
<td>27.5</td>
<td>27.5</td>
</tr>
<tr>
<td>300</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>500</td>
<td>22</td>
<td>22</td>
</tr>
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</table>

Decimation filters bit length: 32bit
FIR filters bit length: 25bit

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</tr>
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<td>40</td>
<td>40</td>
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<td>37.5</td>
<td>37.5</td>
</tr>
<tr>
<td>30</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>50</td>
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<td>30</td>
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<td>22</td>
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Analysis of the bit length for DSP

NF calculation of 22bit decimation filter and 25bit FIR filter

Decimation filters bit length: 22bit
FIR filters bit length: 25bit

![Graph showing NF calculation for ADC+DSP and ADC Only]
Analysis and design for front-end

Calculating the NF and gain for front-end in order to keep receivers NF of 8dB.

**NF=28.6dB**

<table>
<thead>
<tr>
<th>NF for front-end [dB]</th>
<th>Necessary gain for front-end [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.3434046</td>
</tr>
<tr>
<td>1</td>
<td>21.5605299</td>
</tr>
<tr>
<td>2</td>
<td>21.8502767</td>
</tr>
<tr>
<td>3</td>
<td>22.244863</td>
</tr>
<tr>
<td>4</td>
<td>22.7988092</td>
</tr>
<tr>
<td>4.5</td>
<td>23.1642654</td>
</tr>
<tr>
<td>5</td>
<td>23.6146253</td>
</tr>
<tr>
<td>5.5</td>
<td>24.1826455</td>
</tr>
<tr>
<td>6</td>
<td>24.9232352</td>
</tr>
<tr>
<td>6.5</td>
<td>25.9393661</td>
</tr>
<tr>
<td>7</td>
<td>27.4622541</td>
</tr>
<tr>
<td>7.5</td>
<td>30.2297457</td>
</tr>
</tbody>
</table>

**Specification goal for SDR**

<table>
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<tr>
<th>Sensitivity (NF)</th>
<th>NF : 8dB</th>
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<tr>
<td>IP3 in &amp; IP2 in</td>
<td>IP3in : +20dBm</td>
</tr>
<tr>
<td></td>
<td>IP2in : +60dBm</td>
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<table>
<thead>
<tr>
<th>Sensitivity (NF)</th>
<th>NF : 14dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP3 in &amp; IP2 in</td>
<td>IP3in : +30dBm</td>
</tr>
<tr>
<td></td>
<td>IP2in : +70dBm</td>
</tr>
</tbody>
</table>
Amplifier Design

**Base amplifier** for RF amp

Basic schematic of the amp

Push-pull layout

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>9.2dB @14MHz</td>
</tr>
<tr>
<td>NF</td>
<td>3.7dB @14MHz</td>
</tr>
<tr>
<td>IP3in</td>
<td>45.9dBm @14MHz</td>
</tr>
<tr>
<td>IP2in</td>
<td>82.2dBm @14MHz</td>
</tr>
</tbody>
</table>
Analysis and design for front-end

The IP3 in

\[
\text{IP3 in} = \frac{(\text{Two tone level - IMD level})}{2} + \text{Input} \\
= \frac{9.2\,[\text{dBm}] - (-82.50\,[\text{dBm}])}{2} + 0\,[\text{dBm}] = 45.85\,[\text{dBm}] \quad (14)
\]

The IP2 in

\[
\text{IP2 in} = (\text{Two tone level - IMD level}) + \text{Input} \\
= 9.2\,[\text{dBm}] - (-73.00\,[\text{dBm}]) + 0\,[\text{dBm}] = 82.2\,[\text{dBm}] \quad (16)
\]

NF = 3.7 dB @ 14 MHz

Gain = 9.2 dB @ 14 MHz
Amplifier Design

RF amplifier for front-end

Push-pull layout

Gain | 26dB @14MHz
---|---
NF | 4.1dB @14MHz
IP3in | +27.9dBm @14MHz
IP2in | +71.1dBm @14MHz
Analysis and design for front-end

The IP3

\[
\text{IP3} = \frac{\text{Two tone level} - \text{IMD level}}{2} + \text{Input}
\]

\[
= \frac{15.8 \text{[dBm]} - (-60.0 \text{[dBm]})}{2} + (10) \text{[dBm]} = 27.9 \text{[dBm]} \quad (17)
\]

The IP2

\[
\text{IP2} = (\text{Two tone level} - \text{IMD level}) + \text{Input}
\]

\[
= 15.8 \text{[dBm]} - (-65.3 \text{[dBm]}) + (10) \text{[dBm]} = 71.1 \text{[dBm]} \quad (18)
\]
Performance characteristics of the SDR

**Frequency Range**
- 500kHz to 30MHz

**NF (high sensitivity mode)**
- 8.0dB (typ)

**NF (low distortion mode)**
- 14.0 dB (typ)

**IP3 (in-band) (high sensitivity)**
- +23dBm (typ)

**IP3 (in-band) (low distortion)**
- +30dBm (typ)

**IP2 (in-band) (high sensitivity)**
- +70dBm (typ)

**IP2 (in-band) (low distortion)**
- +80dBm (typ)

**Receiving band width (wide)**
- 1.25MHz to 10MHz

**Receiving band width (narrow)**
- 150Hz to 500kHz

**Signal linearity**
- >130dB

**RF limit level for receiving**
- -13dBm

**IQ data output (Max)**
- 24bit each
Thank you!

Any questions?