Cognitive Radio opportunities and RF Receiver Challenges.

Yann Le Guillou
Overview

- Evolution Trends of Spectrum Usage
- TV White Spaces
  - Interest
  - Usage example
  - Hardware Radio Challenges
- Cognitive Radio and ADCs challenges and directions
- Receiver challenges
- Some Solution Directions
  - RF filtering Interference
  - Interference Cancellation
  - Digital assistance of dirty RF
- Conclusion

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Gap Between Wireless Traffic Supply and Demand Widens

- Trend: Increasing growth of mobile traffic
  - More than 4 billion mobile phone users today and growing at a startling rate
  - “7 trillion wireless device serving 7 billion people in 2017” – Wireless World Research Forum
  - Mobile Internet traffic handled by mobile operators grow from 7 billion megabytes worldwide [in 2008] into 63 billion megabytes in 2013 (CAGR 54%)” – Informa
Spectrum Scarce?

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Spectrum not well managed in time domain and in geographical area
Unlicensed secondary re-use of TV broadcast spectrum
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Why the interest in TV White Space?

- **Switch-off of Analog TV**
  - The release underutilized and valuable spectrum in UHF bands that can be used for next generation wireless network and low-cost communications

- **UHF Signal properties**
  - More spectrum available!
  - Good propagation ability (long range for low power)
  - Good building penetration (e.g. public safety applications)
General Agreement at high level

- Frequency: 470-698MHz
- Channels: 6-8MHz
- Incumbent protection (WSDB)
- Power Levels and control of secondary users

... but Roadblocks are still there

- harmonization across regulatory regimes are difficult
- Industry is still waiting...
Application Example – Rural Broadband

Outstanding propagation characteristic in the VHF/UHF reduce build-out costs and open era to Rural Broadband & Smart Agriculture

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Example - Offload 3G/4G Traffic

Feasibility study Central London

- 1 km² area in Central London,
- 5 000 homes
- 100 mW (WiFi), 20 mW (TVWS)

5.8GHz

2.4GHz

~0.8GHz

“Super-WiFi” in TV White Spaces: similar coverage as mobile broadband

with just a 20% deployment density and 10-50 times faster than 3G

[Maziar Nekovee, BT]
TVWS Radio Hardware Challenges

- **PHY Receiver Challenge**
  - Wide dynamic range (especially in ADC)
  - Highly sensitive
  - Interference Management
  - Spectrum Sensing over wide frequency range

- **PHY Transmitter Challenge (=SDR + extreme frequency agility)**
  - Spectral Emission
  - Low Power

- **Both PHY**
  - Frequency Agility: Operation Frequency range from ~ 10’ MHz to several GHz
  - Bandwidth Agility
  - Flexibility/upgradability: Standard agnostic transceiver able to Rx/Tx current and future standards
  - Low cost
  - Low Power
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ADC Bandwidth versus SNDR

Cognitive Radio (6GHz and 100dB)

TV WS (900MHz and 100dB)

Jitter=1ps\textsubscript{RMS}

Jitter=10fs\textsubscript{RMS}

Jitter=100fs\textsubscript{RMS}

Jitter=1ps\textsubscript{RMS}

Far from feasible ...

[Murmann- ADC Performance Survey 1997-2014]
http://www.stanford.edu/~murmann/adcsurvey.html

\textbf{SNDR} @ \textbf{f\textsubscript{in,hf}} [dB]
Energy/fs versus SNDR

Today, FOM=1pJ/conv-step for high speed high SNDR
Required ADC Power (w/o clocking system)

Suppose:

- 1pJ/conversion
- Signal -100dBm ... 0dBm ↔ 17 bits

- **Cognitive Radio**
  
  50MHz-6GHZ ↔ $f_{\text{sample}} \approx 12$GHz
  
  $P = E_{\text{conv}} f_{\text{sample}} 2^{\#\text{bits}} = 10^{-12} \cdot 12 \cdot 10^9 \cdot 2^{17} \approx 1.5kW$

- **TVWS Radio**
  
  700MHz-900MHZ ↔ $f_{\text{sample}} \approx 1.8$GHz
  
  $P = E_{\text{conv}} f_{\text{sample}} 2^{\#\text{bits}} = 10^{-12} \cdot 1.8 \cdot 10^9 \cdot 2^{17} \approx 235W$

RF-ADC most flexible « software-defined » receiver far from being Green today

....but also $\sim 225x$ (1.8GS/s for 8MHz channel) to $1000x$ (10GS/s for ~10MHz channel) overkill
Required clock power

Suppose
- 100dB SNDR ↔ Clock Jitter, $\sigma_t \sim 1\text{fs}_{\text{RMS}}$ (see slide 16)
- State of the art FOM$_{\text{PLL}}$~ -230dB

where
$$\text{FOM}_{\text{PLL}} = 10 \log \left[ \left( \frac{\sigma_{t,\text{PLL}}}{1\text{s}} \right)^2 \cdot \frac{P_{\text{PLL}}}{1\text{mW}} \right]$$

Then $P_{\text{PLL}} \sim 10 \text{kW} !!$

Not achievable today neither tolerable for low power.
Today 20mW dissipation is tolerable, resulting in
$\sim 0.7\text{ps}_{\text{RMS}}$ clock jitter
Down-conversion / filtering required

This radio is still very flexible with software

IMEC-Renesas- 11b- 410MSPs – TI SAR ADC - ~1ps\textsubscript{RMS} jitter

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TI-SAR ADC

- 2x time-interleaved pipeline SAR ADC in 28nm CMOS
- 11-bit, 0-410MSPs, 2.1mW
- 6.5fJ/conv-step
- Power consumption scale linearly with sampling
- SNDR=55dB@205MHz
- On-chip calibration engine for gain and offset errors

[Verbruggen, VLSI, 2013]

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To push TI-ADC SNDR above 11-bits need to calibrate frequency dependant spurs due to time-skew and bandwidth mismatches.

Digital calibration is required to get the right accuracy.

Estimation accuracy needed to reach the desired SFDR of 90 dB in 99.9% of cases with a 4TI-ADCs, an input signal \( x(t) = 1.5 \sin(2\pi f_0 t) \), \( f_0 = 146.29 \)MHz and \( f_s = 320 \)MHz.

\[
\frac{Y_{AC}(f)}{f_s} = \sum_{k=-\infty}^{+\infty} \frac{H(\cdot)X(\cdot) + \frac{1}{M} \sum_{m=0}^{M-1} \Delta_m H(\cdot) X(\cdot)_{f-kf_s}}{f-kf_s} + \sum_{k \neq 0(M)}^{+\infty} \frac{1}{M} \left[ \sum_{m=0}^{M-1} e^{-\frac{mM(\Delta_m f_c)}{f_s}} \right] X(\cdot)_{f-kf_s} \tag{4}
\]

\[
\frac{\Delta_m H(f)}{H(f)} = \frac{\Delta_m G}{G} - j2\pi f \left( \Delta_{m_{\text{skew}}} - \frac{1}{2\pi f_c} \Delta_m f_c \right)
\]

<table>
<thead>
<tr>
<th>Accuracy [ppm]</th>
<th>Gain</th>
<th>Offset</th>
<th>Time-Skew</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>120</td>
<td>7</td>
<td>540</td>
<td></td>
</tr>
</tbody>
</table>

[Paquelet, Kamdem De Teyou, Le Guillou, IEEE NEWCAS, 2013]
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**Interference Management Challenge**

- TVWS Radio are envisioned to be **capable of sensing** and reasoning about the **operating radio environments** and thereby **autonomously adjusting** their transceiver **parameters** to exploit the underutilized radio resources in a dynamic fashion.

- Cognitive Radio operates in **interference-intensive environments**.

- Minimum interference is therefore essential to the **coexistence of Primary and TVWS Radio** (Secondary System).

<table>
<thead>
<tr>
<th>A</th>
<th>Interference from CR to Primary networks (CR Transmitter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Interference from Primary networks to CR networks (CR Receiver)</td>
</tr>
<tr>
<td>C</td>
<td>Interference from CR to CR (CR Transmitter and Receiver)</td>
</tr>
</tbody>
</table>
Additional RF impairment for TVWS device

- On top classical Rx noise due to Receiver RF Front End Impairment (Phase noise, linearity, Noise etc.)
- **Tx** noise due to Tx leakage
- **IntPrimary** due to Primary Network Interferers
- **CRNetworks** due to all CR networks

![Diagram of RF impairment components]

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Linearity requirements challenges

Assumption: 2 tones at Pin [dBm]
IM level equal to Noisefloor N=-100dBm

Required IIP3 [dBm]

\[ \text{IIP3}_{\text{req}} = \frac{3}{2} P_{\text{in}} - \frac{1}{2} N \]

Required IIP2 [dBm]

\[ \text{IIP2}_{\text{req}} = 2 \cdot P_{\text{in}} - N \]

Challenge: **high linearity** broadband receivers
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Tunable RF filtering challenges

- Frequency selection by coil L & capacitor C
- Tuned mechanically by variable plate-capacitor C

Center frequency: \( f_c \propto \frac{1}{\sqrt{L \cdot C}} \)

- On-chip CMOS filters:
  - limited Q inductors =\( f_c/\text{bandwidth} < 15 \) (lossy, bulky, not flexible)
  - Limited \( f_c \) tuning-range \( \sim 30\% \)
  - Active inductors (noisy, non-linear)

- Alternative Idea
  - Do not use inductor
  - Switch & capacitors are very linear
  - Switch & capacitors scale with CMOS
N-path filter concept

- N signal paths switched series R-C

\[ T_{ON} = T_{LO}/N \]

- In-band \( (f_{RF} \approx f_{LO}) \): High \( Z_{RF} \)
- Out of band: low \( Z_{RF} \) (Short circuit)

\[ V_{RF}, f_{RF} = f_{LO} \]

\[ V_{RF}, f_{RF} = 1.5f_{LO} \]

\[ V_{BB1} \neq 0 \]

\[ V_{BB1} = 0 \]
N-path filter properties

Frequency filtering @ RF

Frequency filtering @ baseband

CMOS:
Switches & capacitors

High-Q RF filter
Linear
Widely tunable

\[ T_{ON} = \frac{T_{LO}}{N} \]

\[ \phi_1, \phi_2, \phi_N \]

\[ V_{BB1}, V_{BB2}, V_{BBN} \]

\[ C \]

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Filtering properties: flexibly tunable

6th order 8-path

Table:

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit Type</td>
<td>CMOS Tech. [nm]</td>
<td>Filter</td>
<td>Receiver</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>65nm CMOS</td>
<td>65</td>
<td>65</td>
<td>250</td>
<td>65</td>
<td>40</td>
<td>65</td>
<td>40</td>
</tr>
<tr>
<td>Frequency range [GHz]</td>
<td>0.1-1.2</td>
<td>0.4-1.2</td>
<td>2.14</td>
<td>0.1-1</td>
<td>0.4-6</td>
<td>2</td>
<td>0.08-2.7</td>
</tr>
<tr>
<td>IIP2(OOB) [dBm]</td>
<td>+26</td>
<td>+29</td>
<td>N/A</td>
<td>+142</td>
<td>+10</td>
<td>-6.3</td>
<td>+13.5</td>
</tr>
<tr>
<td>BMV/CEO [dBm]</td>
<td>+7</td>
<td>N/A</td>
<td>N/A</td>
<td>+2</td>
<td>-8</td>
<td>N/A</td>
<td>&lt;0</td>
</tr>
<tr>
<td>NF [dB]</td>
<td>2.8</td>
<td>10</td>
<td>19</td>
<td>3-5</td>
<td>3</td>
<td>5.8</td>
<td>2</td>
</tr>
<tr>
<td>Gain [dB]</td>
<td>+25</td>
<td>+3.5</td>
<td>0</td>
<td>-2</td>
<td>+70</td>
<td>+55.8</td>
<td>+70</td>
</tr>
<tr>
<td>BW [MHz]</td>
<td>8</td>
<td>20</td>
<td>60</td>
<td>35</td>
<td>4</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Ripple [dB]</td>
<td>&lt;0.6</td>
<td>&lt;0.4</td>
<td>0.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Filter order</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td>2</td>
<td>2 @RF</td>
<td>6</td>
<td>2 @RF</td>
</tr>
<tr>
<td>Stopband rejection[dB]</td>
<td>59</td>
<td>&gt;55</td>
<td>&gt;30</td>
<td>15</td>
<td>&lt;15 @RF</td>
<td>50</td>
<td>&lt;15 @RF</td>
</tr>
<tr>
<td>VDD (Volts)</td>
<td>1.2</td>
<td>1.2/2.5</td>
<td>2.5</td>
<td>1.2</td>
<td>2.5</td>
<td>1.2/2.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Power [mW]</td>
<td>15-48mA</td>
<td>12.8-21.4</td>
<td>17.5</td>
<td>2-20</td>
<td>30-55mA</td>
<td>21mA</td>
<td>27-60mA</td>
</tr>
<tr>
<td>Area [mm²]</td>
<td>0.27</td>
<td>0.12</td>
<td>3.51</td>
<td>0.07</td>
<td>2</td>
<td>0.76</td>
<td>1.2</td>
</tr>
</tbody>
</table>

1) I_{diss} = 11.7mA, I_{dch} = 3.36mA

[Darvishi, van der Zee, Nauta, ISSCC 2013]
Interference Cancellation Techniques ...

Take a look in the past ...

Hedy Lamarr

25-Year Old Hollywood Star invents frequency hopping
10th June 1940

Frequency Hopping according to the free IM spot....
Exploit the spectrum Sensing and use the Free IM Spots

- RF Bandpass Filter
- Third order distortion products
- Number of IM3 Free spots = 6

- Select the IM3-free spots

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Bio Inspired RF Silicon Cochlea 100MHz-10GHz

...and in the future

This diagram shows the wiring layout of the radio chip designed by Rahul Sarapeshkar to mimic the human cochlea.

IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 44, NO. 6, JUNE 2009
Capitalize on trend in the embedded digital core processor

- Today’s mobile device (Tablet PC etc.) have more processing capabilities than the original supercomputers!
- Capitalize on it to bring the required flexibility and assist dirty RF
Some digitally assist analog and RF impairment directions ...

- Linearity (IP2, IP3) enhancement techniques
- Noise reduction by cross-correlation techniques (as in Spectrum Analyser)
- I and Q magnitude and phase imbalance
- TI-ADC impairments
- Clock spur cancellation ...
Example - clock spur cancellation

- Clock spur reduced by 40dB
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- Cognitive Radio receiver challenges are interdisciplinary in nature (RF, analog, digital signal processing, ...)

- Capitalize on CMOS technology and DSP but think out of the box
  - Make optimum use of Switches and Cap in CMOS technologies to built RF functions
  - Make optimum use of technology speed and high speed clock possibility
  - Digitally assist dirty RF & Analog to boost the performances