Evolution of the Software-Defined Radio (SDR) Receiver

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The Need

Quad-band GSM
GPRS
Wideband CDMA
EDGE
GPS
Bluetooth
802.11b ...

Cram down the funnel of functions

- Large number of independently developed radio boards, all squeezed into a small mobile device ...
- You see one antenna, there are actually 3 or 4 ...
- Next month there will be a new wireless application
- Where will this end??
The Software Defined Radio

- Needs 12b, 10 GS/s A/D Converter (ADC)

- Ultimate in flexibility!

- Low power solution not in sight, Moore’s law doesn’t help
Goals for today’s SDR Transceiver

Table 1: RX frequency bands

<table>
<thead>
<tr>
<th>Center Frequency Band [MHz]</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>460.4-467.6</td>
<td>2G,3G</td>
</tr>
<tr>
<td>488.8-496</td>
<td>2G,3G</td>
</tr>
<tr>
<td>869-894</td>
<td>2G-3G</td>
</tr>
<tr>
<td>925-960</td>
<td>2G-3G</td>
</tr>
<tr>
<td>1805-1880</td>
<td>2G-3G</td>
</tr>
<tr>
<td>1881-1897</td>
<td>2G-3G</td>
</tr>
<tr>
<td>1900-1920</td>
<td>3G</td>
</tr>
<tr>
<td>1930-1990</td>
<td>2G-3G</td>
</tr>
<tr>
<td>2010-2025</td>
<td>3G</td>
</tr>
<tr>
<td>2110-2170</td>
<td>3G</td>
</tr>
<tr>
<td>2170-2200</td>
<td>3G</td>
</tr>
<tr>
<td>2400-2484</td>
<td>ISM (11g/b, ..)</td>
</tr>
<tr>
<td>5150-5350</td>
<td>UNII (11a,cordless)</td>
</tr>
<tr>
<td>5725-5825</td>
<td>UNII (11a,cordless)</td>
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Table 1: TX frequency bands

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<th>Standard</th>
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<tr>
<td>450.4-457.6</td>
<td>2G,3G</td>
</tr>
<tr>
<td>478.8-486</td>
<td>2G,3G</td>
</tr>
<tr>
<td>824-849</td>
<td>2G-3G</td>
</tr>
<tr>
<td>894.1-915</td>
<td>2G-3G</td>
</tr>
<tr>
<td>1710-1785</td>
<td>2G-3G</td>
</tr>
<tr>
<td>1881-1897</td>
<td>2G-3G</td>
</tr>
<tr>
<td>1900-1920</td>
<td>3G</td>
</tr>
<tr>
<td>1850-1910</td>
<td>2G-3G</td>
</tr>
<tr>
<td>1920-1980</td>
<td>3G</td>
</tr>
<tr>
<td>1980-2010</td>
<td>3G</td>
</tr>
<tr>
<td>2010-2025</td>
<td>3G</td>
</tr>
<tr>
<td>2400-2484</td>
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What does the spectrum look like actually?

- Strong signals in only a few bands, and near base stations
- Worst-case blocker profiles are pessimistic

Watkins, Bristol U., 2001
What’s wrong with this concept?

- Mitola’s SDR can receive every band and channel concurrently!
- May be important for military, not necessary for civilian uses

<table>
<thead>
<tr>
<th>Standard</th>
<th>Modulation Scheme</th>
<th>Channel BW (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM</td>
<td>GMSK</td>
<td>0.200</td>
</tr>
<tr>
<td>EDGE</td>
<td>8PSK</td>
<td>0.200</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>GFSK</td>
<td>1</td>
</tr>
<tr>
<td>CDMA IS95</td>
<td>QPSK CDMA</td>
<td>1.25</td>
</tr>
<tr>
<td>WCDMA/CDMA2000</td>
<td>QPSK/16QAM/CDMA</td>
<td>1.25-5</td>
</tr>
<tr>
<td>802.11a/g</td>
<td>OFDM</td>
<td>20</td>
</tr>
<tr>
<td>802.11n</td>
<td>OFDM</td>
<td>10-20-40</td>
</tr>
</tbody>
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Modified SDR

① Good enough to receive one channel at a time, but from any band, with any channel bandwidth, and any modulation

② Tunes channel of interest to zero IF

③ Wideband receiver (no RF preselect)
What’s inside the Digital Receiver?

Everything is software controlled - clock rate, no. of taps

Sample rate conversion causes aliasing ...

Davies, 2000
How to make the RF/analog flexible?

- Push as much to digital as possible
  - With ADCs that dissipate milliwatts!
- Model the RF/analog signal processing on digital receiver

- Let’s design an A/D centric RX, and work upstream towards the antenna
- Budget 10mW for A/D—today this gets us:
  - 8b, 40 MHz Nyquist ADC, or
  - 14b, 10 MHz Delta-Sigma ADC with 200 kHz bandwidth

- Choose best ADC for channel bandwidth and blocker profile
- Develop RX for GSM (200 kHz) and 802.11g (20 MHz)
Digital AGC to the max

- Variable gain amplifiers are hard to design in scaled CMOS
- What is bare minimum analog variable gain, say for GSM?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{\text{max}}$</td>
<td>-15 dBm</td>
</tr>
<tr>
<td>$S_{\text{min}}$</td>
<td>-102 dBm</td>
</tr>
<tr>
<td>$A_{\text{min}}$</td>
<td>12</td>
</tr>
<tr>
<td>$A_{\text{max}}$</td>
<td>43</td>
</tr>
<tr>
<td>PAR</td>
<td>4 dB</td>
</tr>
<tr>
<td>FS</td>
<td>-1 dBm</td>
</tr>
<tr>
<td>SNR</td>
<td>9</td>
</tr>
<tr>
<td>NQ</td>
<td>-82 dBm</td>
</tr>
<tr>
<td>Margin</td>
<td>13 dB, 0.2 dB loss</td>
</tr>
</tbody>
</table>

- 31 dB analog variable gain encompasses 87 dB input dynamic range
- DSP assumes rest of the burden
- Good use of surplus A/D dynamic range
Where to sample the wideband input?

• As soon as the signal of interest is at zero IF ...
• Clock-driven discrete-time analog signal processing gives greatest flexibility
• With 5 GHz-wide input band, what should be the sampling frequency?
  - Only the channel at zero IF is of interest
  - Everything else is unwanted
  - But we’ll need an anti-alias filter with 100:1 range in cutoff if we sample 200 kHz to 20 MHz wide channels—impractical
**Lowpass Sampler w/ Internal Anti-Alias**

- Main-lobe passes wanted signal at DC
- Side-lobes roll off with 20 dB/decade
- Notches @ nf_s for anti-aliasing
- Wider stop-band with higher f_s

Rectangular Window Integration

\[
|H(f)| = \frac{g_m T_s}{C} \left| \frac{\sin(\pi T_s f)}{\pi T_s f} \right|
\]

[Yuan, 2000]
Bring Down the Sample Rate (in Analog)

- Initial sample rate may be very high, to protect the wanted channel
- A/D conversion at this rate wastes power, as wanted signal band is much lower
- Analog decimation filter? Yes ...

Lindfors, et al., 2003
Helsinki University
Just Enough Analog Filtering

- Filter must be developed based on profile of in-band and out-of-band blockers
- Remember, there is no RF prefilter in our SDR
• Channel of interest lies in 2.4 GHz band, 20 MHz wide
• Choose initial sample rate of 480 MHz in windowed integrator (Why? We'll see in the next slide)
• Now first aliasing blocker is a strong CDMA cellular channel
• $sinc()$ alone cannot attenuate it sufficiently (–80 dB) across 20 MHz
Two passive RC poles at the mixer load gives monotonic attenuation across frequency (justifies $f_s = 480$ MHz)

Pole frequencies are programmable

Small droop in channel bandwidth around DC

Filter violates specifications between 200-300 MHz
• Filter meets specs (at $f_s=480$ MHz), but...

• Sample rate still too high for ADC, considering channel is only 20 MHz wide

• Must decimate with suitable filter to avoid aliasing ...
Evolution of RX Filter (802.11g) – 4

- Decimate by 4
- Now, however, new filter spec applies with 4× more anti-alias notches
- Specification met by $sinc^2()$ decimation FIR filter
- Should decimate further to lower power in ADC — output sample rate 120 MHz still too high for bandwidth of interest from 0 ~10 MHz
• Decimate by 3
• New filter spec has 3× more anti-alias notches
• Specification met by sinc() decimation FIR filter
• Now output sample rate of 40 MHz and resolution of 8b realizable by ADCs dissipating ~10 mW
Filter Realization

From mixer
2.5~10mS

$Sinc^2$→

D-T Pole

$\phi_{1r}$

$\phi_1$

$\phi_2$

$\phi_3$

$\phi_4$

$\phi_5$

$\phi_6$

$\phi_7$

$\phi_8$

$\psi_{1,3}$

$\psi_1$

$\psi_2$

$\psi_3$

$\psi_4$

$\psi_{2,4}$

$C_u=200f\sim1.6pF$

11g,GSM

$C_{IIR}=25C_u,200C_u$

$C=C_u,2C_u$

To A/D Converter

GSM Gain 6~36 dB

11g Gain -4~26 dB
The ultimate CMOS mixer

6.4mA from 2.5V

- Passive FETs commutate signal current only
- Current source drive, low impedance buffer $\Rightarrow$ no voltage swing on FETs
- Main contributors to 2$^{nd}$ order nonlinearity:
  - Low frequency distortion of transconductor: Suppressed by $C_c$
  - Switch offset: Triode operation & low input impedance buffer
  - RF-LO feedthrough
- IIP2=+77dBm (@-20dBm)
- DSB NF~13dB due to $g_m$, flicker noise corner<10KHz (large gate area buffer)
Harmonic mixing
Unique to wideband RX

- Hard switching mixer gives high conversion gain—good
- **Harmonics** in square-wave commutation downconvert in-band channels, e.g. 900 MHz also downconverts 2.7 GHz and 4.5 GHz—BAD!

- 3-path mixer better approximates sine
- $3^{rd}$, $5^{th}$ harmonic rejection is limited by phase error and gain mismatch

<table>
<thead>
<tr>
<th>Harmonic Rejection</th>
<th>dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd Harmonic Rejection</td>
<td>38</td>
</tr>
<tr>
<td>5th Harmonic Rejection</td>
<td>40</td>
</tr>
</tbody>
</table>
Ultimate challenge: Wideband LNA

- Departs from conventional narrowband RF practices
- CG provides input match
- CS to provide extra gain & single to differential
- Input matching forms a 3\textsuperscript{rd} order maximally-flat ladder filter, embedding bondwire
- 3\textsuperscript{rd} order maximally-flat LC ladder filter as wideband load
- Measured: 18-20\,dB gain and S11<-10\,dB over 800\,M-5\,GHz
Noise cancellation
Feedforward pre-dates feedback

- CG noise is cancelled at diff. output [Brucoleri, JSSC 2004]
- Noise cancellation has little sensitivity to all parameters and measured NF<3dB [Chehrazi, CICC 2005].
- ~20dB Gain programmability by disabling CS and dumping CG signal current

![Diagram showing noise cancellation circuit with M1, M2, in1, in2, Out, and NF vs. GHz graph]
Wideband Frequency Tuning

- Covers all major bands
- 2 VCOs, only one is active at a time
- 21-33 mA dissipation for different bands
- 3 VCOs can give continuous frequency coverage

- Divide & mux only
- No SSB mixers—unacceptable spurious tones
On-chip Selectivity
Displaces RF preselect filter

802.11g

Wanted 802.11g channel

Measured response

$\frac{f_s}{f_{ADC}} = 480 \text{ MHz, } 4\downarrow \text{ & } 3\downarrow$, $f_{ADC} = 40 \text{ MHz}$

GSM

Filter specification (WCDMA Band)

$\frac{f_s}{f_{ADC}} = 72 \text{ MHz, } 4\downarrow \text{ & } 2\downarrow$, $f_{ADC} = 9 \text{ MHz}$

Spurious Response

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Spurious Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>11g@ 22 MHz</td>
<td>-60dBr</td>
</tr>
<tr>
<td>GSM@ 4.7 MHz</td>
<td>-74dBr</td>
</tr>
</tbody>
</table>

Currents from 1V

| 11g $I_{dc}$ | 13~28 mA |
|  |  |
| GSM $I_{dc}$ | 8~23 mA |
But leaves LNA/Mxr vulnerable
Exposed to intermod from every band

- $n^{th}$ harmonic distortion
  - DCS 1800, 60 dBm IIP2, GSM 900M blocker
- $n^{th}$ harmonic mixing
  - GSM 900, 110dB H2RR, GSM 1900 interferer

- Harmonic distortion and mixing are rare cases and waived by exceptions allowed in standards

- Cross-modulation (AM blocker)
  - GSM RX: -4dBm IIP3 $\rightarrow$ -12dBm WCDMA blocker
  - AM detection (AM blocker)
    - GSM RX: 70 dBm IIP2 $\rightarrow$ -15dBm WCDMA blocker

- Serious problem: AM blocker at any frequency can be harmful
Final Clock-Programmable SDR Receiver

- RX tolerates AM blockers as high as -20dBm with no preselect filter
- Still higher linearity is needed from LNA and mixer

Full RX Chain Summary

<table>
<thead>
<tr>
<th></th>
<th>GSM</th>
<th>802.11g</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF (High Gain) [dB]</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>IIP3 (Mid Gain) [dBm]</td>
<td>-3.5</td>
<td></td>
</tr>
<tr>
<td>IIP2 (Mid Gain) [dBm]</td>
<td>+65</td>
<td>+67</td>
</tr>
<tr>
<td>Power [mW]</td>
<td>18-52</td>
<td>23-57</td>
</tr>
</tbody>
</table>

Active Area ~ 3.8mm²
Future Research

• Linearity, linearity, linearity!
• Concurrent reception of two or three unrelated bands, sharing hardware
• Full duplex operation such as in CDMA (without RF filters?)
• Full system demonstration with digital front-end and baseband—commercial feasibility