SDR Developments,
with an emphasis on the
FlexRadio 6000 series

Weldon Mathews, K8NQ

CRES Meeting, October 29, 2013
Much of this information was made available by

**Greg Jurrens, K5GJ**
VP Sales and Marketing,
FlexRadio Systems

and by

**Scotty Cowling, WA2DFI**
Dayton TAPR Forum, 2013

I can take credit only for the mistakes.
Digital Signal Processing in Software Defined Radios

Taking it to the Next Level

May 29, 2013
Hamfest Presentation

Greg Jurrens, K5GJ
VP Sales and Marketing, FlexRadio Systems
Software Defined ... ?

1. Does the ...? USE software?

2. To what extent is the ...? DEFINED by software?

3. Software Defined Radios

4. Software Defined Antennas (patent)

5. Cognitive Radios
TRENDS IN SDR

Agenda

- What makes a Software Defined Radio (SDR)?
- Emerging SDR System Architectures
- The Network of Things
- Signal Processing & DSP
- Simplicity
Radio RF/IF Architectures

- **Multi-conversion** a.k.a. superheterodyne
  - Your car radio, your TV, any older scanner you have
  - Most every Kenwood, Icom, Ten-Tec, Elecraft and Yaesu on the market today

- **Direct Conversion**
  - FLEX-5000, FLEX-3000, FLEX1500, Elecraft KX3

- **Direct Sampling** a.k.a wideband
  - FLEX-6000, HPSDR
Multi-Conversion

[Example, ICOM 756 Pro]

RF Spectrum

3–15 kHz Roofing Filter

64.455 MHz

455 kHz

36 kHz

ADC

DSP

DET

96 ksp

[Distortion] FlexRadio Systems

Software Defined Radios
Multi-Conversion

The good and bad

+ Adjacent band signal rejection: operate in harsh signal conditions
+ Common, well-accepted design: works well
– Only signals in the final IF can be tuned
– Distortion introduced in each stage of filtering and mixing
– Limited view of spectrum
– For best filtering, requires expensive crystal filters (multiple)
Direct Conversion
or Quadrature Sampling Detection, QSD

[Sometimes called Audio Frequency or Base Band]
Direct Conversion

The good and not-so-good

- Distortion minimized with only one mixer: clear signal — sounds better, less fatigue (less in-band distortion)

- Can show 192kHz to our customers: wide panadapter view

- Low power, high dynamic range: interference mitigation

- Image rejection difficult (balanced IQ mixer, WBIR)

- Better, but still limited view of spectrum
In-Band IMD Comparisons

- FLEX-5000 Direct Conversion QSD
- Roofing Filter Based Down Conversion IF DSP (Radio X)
- Roofing Filter Based Up Conversion IF DSP (Radio Y)
- Roofing Filter Based Up Conversion IF DSP (Radio Z)

200 Hz separation
Filter Shape Factor

- FLEX-5000
- Note Brick Wall & Flatness
- Radio Y
- Radio Z
- Radio X

Copr. FlexRadio Systems 2009
Direct **Sampling** Benefits

- + Distortion minimized (ADC @ antenna): best signal clarity
- + n-Receivers, n-Panadapters and varying widths see more bands, more receivers
- + Extremely high dynamic range: operate in worst conditions
- + Extreme flexibility through reprogrammability (*ultimate* SDR): future benefits
- – **Technically challenging to design**

Further, a software radio should have as little hardware as possible.  
Direct Sampling Converter Chain

Further, a software radio should have as little hardware as possible.
Direct Sampling
It’s all good!

245.76 MHz

There are still mixers and filters, but they are all math and “perfect” in DSP
Digital Down Conversion

In digital signal processing, a digital down-converter (DDC) converts a digitized real signal centered at an intermediate frequency (IF) to a base banded complex signal centered at zero frequency.

FLEX-6000 Signature Series Hardware Architecture
Spectral Capture Unit

SmartSDR™ Control and DSP

Additional FLEX-6000 Transceivers

Internet

FlexRadio Systems
Software Defined Radios
Direct Sampling Radios

![Direct Sampling Radios Diagram](image)

**FLEX-6000**

**GEN3**

**RF DSP** --- **CTRL**
Other Direct Sampling Radios

- HPSDR
- Hermes
- HPSDR GEN1

RF DSP — DSP CTRL

FlexRadio Systems
Software Defined Radios
### Amateur Radios

**How Much Signal Processing Power is There?**

| BRAND A | Texas Instruments TMS320VC33 | 0.120 GFLOPS |
| BRAND B | Texas Instruments TMS320C6713 | 0.450 GMAC |
| BRAND C | Texas Instruments TMS320C6713 x3 + TMS320C6711 | 1.350 GMAC |
| BRAND B | Texas Instruments TMS320C6727B x2 | 1.350 GMAC |
| FLEX-6500 | Texas Instruments TMS320C6A8167 + XC6VLX75T | 1.40 GMAC |
| FLEX-6700 | Texas Instruments TMS320C6A8167 + XC6VLX130T | 317 GMAC |

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*FlexRadio Systems*

*Software Defined Radios*
Signal Processing

CRAY-1

- 1976
- $5,000,000
- 0.08 GFLOPS
- $62M / GFLOP
Signal Processing

CRAY-2

- 1985
- $17M
- 3.9 GFLOPS
- $4.3M / GFLOP
Signal Processing

**CRAY X1**

- 2002
- $2.5M
- 205 GFLOPS
- $12,000 / GFLOP

[Ohio Supercomputer now at 154 TeraFLOPS or 154,000 GFLOPS]
Signal Processing

FLEX-6700

- 2012
- $6,999
- 121 GFLOPS
- $57.84 / GFLOP
## Computing Power Summary

<table>
<thead>
<tr>
<th>Name</th>
<th>Year</th>
<th>Cost</th>
<th># GFLOPS</th>
<th>Cost/GFLOP</th>
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</thead>
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<tr>
<td>Cray-1</td>
<td>1976</td>
<td>$5M</td>
<td>0.08 GFLOPS</td>
<td>$62m/GFLOP</td>
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<tr>
<td>Cray-2</td>
<td>1985</td>
<td>$17M</td>
<td>3.9 GFLOPS</td>
<td>$4.3M/GFLOP</td>
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<tr>
<td>Cray X1</td>
<td>2002</td>
<td>$2.5M</td>
<td>205 GFLOPS</td>
<td>$12K/GFLOP</td>
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<tr>
<td>Flex-6700</td>
<td>2012</td>
<td>$7K</td>
<td>121 GFLOPS</td>
<td>$57.84/GFLOP</td>
</tr>
</tbody>
</table>
FPGA:
Field Programmable Gate Array

- Massive DSP Power
- Can’t build a Direct Sampling Receiver without one!
- >90% of the FLEX-6000 Power
What is a Field Programmable Gate Array, FPGA?

FPGAs are programmable semiconductor devices that are based around a matrix of Configurable Logic Blocks (CLBs) connected through programmable interconnects. As opposed to Application Specific Integrated Circuits (ASICs), where the device is custom built for the particular design, FPGAs can be programmed to the desired application or functionality requirements.

http://www.xilinx.com/fpga/index.htm
Figure 2. The Different Parts of an FPGA
FPGAs, Why Bother?

The seemingly simple task of multiplying two numbers can get extremely resource intensive and complex to implement in digital circuitry.

To provide some frame of reference, Figure 7 shows the schematic drawing of one way to implement a 4-bit by 4-bit multiplier using combinatorial logic.

BUT all these operations are done in ONE clock cycle! (Thanks to Doug W8NFT for that update.)
Flex 6700 uses the Xilinx Virtex-6 FPGA

<table>
<thead>
<tr>
<th>Features</th>
<th>Artix™-7</th>
<th>Kintex™-7</th>
<th>Virtex®-7</th>
<th>Spartan®-6</th>
<th>Virtex-6</th>
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<tr>
<td>Logic Cells</td>
<td>215,000</td>
<td>480,000</td>
<td>2,000,000</td>
<td>150,000</td>
<td>760,000</td>
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<tr>
<td>BlockRAM</td>
<td>13Mb</td>
<td>34Mb</td>
<td>68Mb</td>
<td>4.8Mb</td>
<td>38Mb</td>
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<tr>
<td>DSP Slices</td>
<td>740</td>
<td>1,920</td>
<td>3,600</td>
<td>180</td>
<td>2,016</td>
</tr>
<tr>
<td>DSP Performance (symmetric FIR)</td>
<td>930GMACS</td>
<td>2,845GMACS</td>
<td>5,335GMACS</td>
<td>140GMACS</td>
<td>2,419GMACS</td>
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<tr>
<td>Transceiver Count</td>
<td>16</td>
<td>32</td>
<td>96</td>
<td>8</td>
<td>72</td>
</tr>
<tr>
<td>Transceiver Speed</td>
<td>6.6Gb/s</td>
<td>12.5Gb/s</td>
<td>28.05Gb/s</td>
<td>3.2Gb/s</td>
<td>11.18Gb/s</td>
</tr>
<tr>
<td>Total Transceiver Bandwidth (full duplex)</td>
<td>211Gb/s</td>
<td>800Gb/s</td>
<td>2,784Gb/s</td>
<td>50Gb/s</td>
<td>536Gb/s</td>
</tr>
<tr>
<td>Memory Interface (DDR3)</td>
<td>x4 Gen2</td>
<td>Gen2x8</td>
<td>Gen3x8</td>
<td>Gen1x1</td>
<td>Gen2x8</td>
</tr>
<tr>
<td>PCI Express® Interface</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Analog Mixed Signal (AMS)/XADC</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>Configuration AES</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>I/O Pins</td>
<td>500</td>
<td>500</td>
<td>1,200</td>
<td>576</td>
<td>1,200</td>
</tr>
<tr>
<td>I/O Voltage</td>
<td>1.2V, 1.35V, 1.5V, 1.8V, 2.5V, 3.3V</td>
<td>1.2V, 1.35V, 1.5V, 1.8V, 2.5V, 3.3V</td>
<td>1.2V, 1.35V, 1.5V, 1.8V, 2.5V, 3.3V</td>
<td>1.2V, 1.5V, 1.8V, 2.5V</td>
<td>1.2V, 1.5V, 1.8V, 2.5V</td>
</tr>
</tbody>
</table>
Signal Processing: Why?

- Many panadapters at once
- Many receivers at once
- Demodulation / Decoding in the radio
- Many bands, One antenna
- Advanced DSP Functions, all in the radio
Flex 5000 with second RX unit using **PowerSDR**
Elegant User Interfaces - SmartSDR (new)
Introduction to SmartSDR display,
by Greg Jurrens, K5GJ
~ 8 minutes

Introduction to Multiple Slice Receivers and Multiple Panadapters by Greg Jurrens, K5GJ
~ 4 minutes
Key SDR Trends

- Direct Sampling Receivers (and Direct Upconversion Transmitters)
- Networking Capabilities
- Massive Signal Processing
- Simplicity and Elegance
Possibilities —
What could you do with:

- Four, six, or eight receivers or panadapters
- The ability to directly decode and display digital modes
- Ethernet connectivity to talk to the world
- The ability to combine receivers in disparate locations
- The ability to transmit locally and listen to yourself remotely
- Access to remote databases on the Internet
- A radio appliance that can be connected via Ethernet to any computer
Does your radio run HERE?
And FlexRadio isn’t alone!

Multiple-Personality SDR:
FPGAs, Reconfigurability and Unconventional Applications

Scotty Cowling, WA2DFI

TAPR Forum
2013 Dayton Hamvention
SDR Applications

CW Skimmer
WSPR Beacons
Chirp Radar
I-F DSP for an existing rig
Vector Network Analyzer
Spectrum Analyzer

Scotty Cowling, WA2DFI
Zephyr SDRstick™ HF2

UDPSDR-HF2

- Type: DDC Receiver
- Antenna: External SMA Antenna Jack
- ADC: 16 bits @ 122.88MSPS
- DAC: 16 bit @ 48KSPS Audio CODEC
- Audio Output: Headphone amplifier
- Frequency Range: LW/MW/HF/VHF 160M – 6M
- Use with BeMicro SDK
- Size: 56x80mm

Cost Goal: ~$400

Scotty Cowling, WA2DFI
SDRstick™ HF2 with BeMicro

Scotty Cowling, WA2DFI  See also
Some Useful Resources

HamCation 2013 Videos by Mike:  [https://www.youtube.com/watch?v=D0gEFw_b8Sc](https://www.youtube.com/watch?v=D0gEFw_b8Sc)
Interview with Greg Jurrens K5GJ, VP Sales & Marketing, Flex Radio,  ~ 3 minutes
Orlando HamCation, Feb 2013

SmartSDR Flex Intro 6000 :  [https://www.youtube.com/watch?v=Vpa3_7kSSwl](https://www.youtube.com/watch?v=Vpa3_7kSSwl)
Greg K5GJ introduces the Panadapter Screen and range of capture  ~ 8 minutes

SmartSDR Flex, slices-panadapters:  [https://www.youtube.com/watch?v=SQjX4jmeCng](https://www.youtube.com/watch?v=SQjX4jmeCng)
Greg K5GJ shows multiple slices and multiple panadapters  ~ 4 mins

Ham RadioNow, Episode 61-Interview:  [https://www.youtube.com/watch?v=yj44qGVjikw](https://www.youtube.com/watch?v=yj44qGVjikw)
Gary KN4AQ interviews Greg K5GJ discussing architecture of 5000 and 6700 Flex,  ~ 1 hr
Orlando HamCation, Feb 2013

Ham RadioNow, Episode 36-Flex SDR architecture:
[https://www.youtube.com/watch?v=xCdxAmMs0C4](https://www.youtube.com/watch?v=xCdxAmMs0C4)
Steve Hicks N5AC, VP Engr, Flex--overview  start at 3:40 ends ~42minutes
Nov 2012 Atlanta
Quadrature, DSP, etc

Fourier Transforms (time and frequency domains)
An unusually good introduction to FTs, including an animated demo.

Robert Lyons, Quadrature Signals: Complex but not Complicated
http://www.ee.nmt.edu/~elosery/lectures/Quadrature_signals.pdf
Excellent discussion of complex numbers and sin-cos functions

Robert Lyons, Sum of two Sinusoids
Good discussion

Gerald Youngblood, AC5OG (now K5SDR) four QEX Articles, 2002-2003
also available at arrl.org QEX site as zip files
Gerald's initial description of SDR
Part 1: General description of DSP in SDRs
Part 2: Visual Basic source code for full-duplex quadrature interface to PC
Part 3: Use DSP to make the PC soundcard into a functional SDR
Part 4: Describes the SDR-1000, FlexRadio's first commercial offering
From Part 1: Further, a software radio should have as little hardware as possible.

Steven W. Smith, The Scientist and Engineer's Guide to Digital Signal Processing
http://dspguide.com/
A 600-page book that can be browsed or downloaded free. Also some great examples of his experience with real-life problems solved with DSP.

FPGAs

Wikipedia descriptions
http://en.wikipedia.org/wiki/Fpga
Excellent introduction

National Instruments, FPGA Fundamentals
Excellent additional details of components

XILINX product description, "What is a FPGA"
http://www.xilinx.com/fpga/index.htm
Thank you for your attention.

Many Thanks to Greg Jurrens and Scotty Cowling for their slides.

My apologizes to both for juggling them a bit and contaminating them with a few of my additions.

Are there questions?