Multiband Public Safety Radio using a Multiband RFIC with an RF Multiplexer-based Antenna Interface

S.M. Hasan and S. W. Ellingson

Wireless at Virginia Tech
Bradley Dept. of ECE, Virginia Tech,
Blacksburg, VA 24060

October 28, 2008
Motivation (1/2)

Frequency Bands:
- VHF LO (25-50 MHz)
- VHF (138-174 MHz)
- 220 MHz
- UHF (406-512 MHz)
- 700 MHz P.S.
- 800 MHz P.S.
- Cellular & PCS
- 2.4 GHz ISM
- 4.9 GHz P.S.

Combine Many Radios into One*
At least 13 bands relevant to Public Safety
x Many channels per band = A lot of radios!
(*Above figure is just a functional description.)

Developing a prototype radio capable of operation over a large range of frequency bands now in use for public safety applications.

Multiband/Multimode Radio
Hasan / Ellingson – October 28, 2008
Motivation (2/2)

For Multiband Multimode Radios (MMR)s

- **Superhet Design-**
  - Power Hungry/ Large/ Complex/ Expensive

- **Direct Conversion Design-**
  - Low Cost/ Small Size/ Low Power/ No IF Filter
  - **Cons:** I/Q imbalance, In band 1/f noise from LO, IP2, Initial BPF

Problems with direct conversion design can now be largely mitigated by:

- Implementing design to be robust to variations
- Exploiting availability of nearby logic to enable radio to tweak chip as needed
- 1/f noise is mitigated by using the combination of DDS and chopping
System Diagram of the Prototype
Motorola Direct Conversion RFIC

**Specs (Verified by VT in Independent Testing)**

<table>
<thead>
<tr>
<th>5 RX Paths (1 output)</th>
<th>90 nm CMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 TX Paths (1 input)</td>
<td>No inductors</td>
</tr>
<tr>
<td>RX F ~ 5 dB</td>
<td>QFN-100</td>
</tr>
<tr>
<td>RX IIP₂ ~ +60 dBm</td>
<td>&lt; 400 mA @ 2.5V (RX+TX)</td>
</tr>
<tr>
<td>RX IIP₃ ~ – 5 dBm</td>
<td></td>
</tr>
</tbody>
</table>

Tunes 100 - 2500 MHz (continuous)

BW: 4.25 kHz – 10 MHz (many steps)

Sideband Rejection ~ 40 dB, up to 60 dB

Internal DDSs for LO generation

Excellent mitigation of 1/f noise


Multiband/Multimode Radio
Hasan / Ellingson – October 28, 2008
Advantages of RFIC-Based Direct Conversion in this Project

- **Scalable** – Same architecture works for reduced or increased number of simultaneous channels/bands (just add/remove chips)

- **Reduced power (extended battery life)** – lower power/channel and unneeded RFICs (or RFIC sections) can be shut down.

- Increased number of channels can be monitored simultaneously, even across bands: Scanner-like capability, “White space” seeker(s) for frequency-agile cognitive radio

- **Con**: Optimization requires calibration and tweaking of many parameters (over a low-bandwidth SPI serial port)
VT Transceiver Board

**Receiver Section:**
Avg. Gain: 48 dB  
I/P 1dB Comp. Pt: -26 dBm  
Sideband Rejection: 29 dB  
Power: 1.1 W (10V@0.11A)

**Transmitter Section:**
Avg. O/P Power: -4 dBm  
O/P 1 dB Comp. Pt: -5 dBm  
Sideband Rejection: 22 dB  
Power: 1.7 W (10V@0.17A)

- No parameter optimization in the RFIC has been performed

- 4-Band Transceiver Board
- Implemented on a 4-layer PCB
- About $100 in parts to implement, excluding PCB.
Antenna Interfacing Idea?

- Sensitivity depends on signal to noise ratio
- External noise can be very strong in practical scenarios, especially at low frequencies (below ~400 MHz)
- If $\gamma$ is large, additional effort to minimize $|\Gamma|$ or $T_{FE}$ will have little effect on sensitivity
- If acceptable $\gamma$ can be achieved for a poor $|\Gamma|$, improvements in $|\Gamma|$ are actually counterproductive, since this complicates the design

Our idea is to design a multiplexer, which may be poorly matched with the antenna impedance, in such a way that the front end is dominated by the external noise and provide acceptable sensitivity.
Antenna Model (1/2)

Thevenin model of antenna

TTG* model of antenna impedance

\[ Z_{\text{ant,Monopole}} = \frac{1}{2} Z_{\text{ant,Dipole}} \]


\[
C_1 = \frac{12.674h}{\log(2h/a) - 0.7245} \text{ pF} \quad C_2 = 2h \left\{ \frac{0.89075}{[\log(2h/a)]^{0.8006}} - 0.861 - 0.02541 \right\} \text{ pF}
\]

\[
L = 0.2h \left[ [1.4813 \log(2h/a)]^{1.012} - 0.6188 \right] \text{ uH}
\]

\[
R = 0.41288[\log(2h/a)]^2 + 3.70377(2h/a)^{-0.02389} - 3.63704 \text{ kOhm}
\]

\[ h = \text{height} \]
\[ a = \text{radius} \]
Antenna Model (2/2)

Circuit model & impedance for a **20 cm** monopole of **5 mm** radius
### External ("Environmental") Noise

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Quiet Rural</th>
<th>Rural</th>
<th>Residential</th>
<th>Business A/B</th>
<th>Celestial¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-30</td>
<td>3.81×10⁴²⁶</td>
<td>2.53×10⁴²⁶</td>
<td>8.54×10⁴²⁶</td>
<td>2.30×10³⁷</td>
<td>1.07×10²³</td>
</tr>
<tr>
<td>30-100</td>
<td>2.86</td>
<td>2.77</td>
<td>2.77</td>
<td>2.77</td>
<td>2.52</td>
</tr>
<tr>
<td>100-130</td>
<td>-</td>
<td>2.53×10⁴²⁶</td>
<td>8.54×10⁴²⁶</td>
<td>2.30×10³⁷</td>
<td>1.07×10²³</td>
</tr>
<tr>
<td>130-250</td>
<td>-</td>
<td>2.77</td>
<td>2.77</td>
<td>2.77</td>
<td>2.52</td>
</tr>
<tr>
<td>250-900</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.46×10³¹⁴</td>
<td>1.07×10²³</td>
</tr>
<tr>
<td>900-3000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.07×10²³</td>
</tr>
</tbody>
</table>

Mean noise temperature, \( T = a f^{-b} \) [K]

\[ \text{External Noise limits receiver’s sensitivity if -} \]

\[ T_{\text{ext}} > T_{FE} \]

Standard deviation with respect to location

\[ \sigma = \text{5.3 dB} \]² \[ \text{5.3 dB} \] \[ \text{4.5 dB} \] \[ \text{6.6 dB} \]³ \[ - \]⁴

¹ Add 2.7 K to account for CMB.
² Decile values not available from [5], using \( D_l = D_u = 6.8 \text{ dB} \) as for “Rural”.
³ Decile values not available from [5], using \( D_l = D_u = 8.4 \text{ dB} \) as for “Business B”.
⁴ Varies over about 2 dB depending on time of day; see [6].


---

**Multiband/Multimode Radio**

Hasan / Ellingson – October 28, 2008
“Optimum” Noise Figure

This is the noise figure required of an amplifier attached to an antenna if the output is to be dominated by external noise by a factor of 10 in 90% of locations of the indicated type.

Optimum in the sense that any lower noise figure does not significantly increase sensitivity (only cost).

These particular results assume lossless, perfectly matched antenna with no ground loss.

- Prevents over-specifying receiver NF
- Can be interpreted as a loosened constraint

Multiband/Multimode Radio
Hasan / Ellingson – October 28, 2008
Transducer Power Gain (TPG):

TPG is defined as the ratio of power delivered by a matching network to a load, to the power delivered to perfectly matched load directly from the antenna.
Results: Before Optimization

- **Solid Line**: Antenna Impedance is assumed as constant 50Ω
- **Dotted Line**: Antenna Impedance is assumed as TTG impedance
Results: After Optimization

**Design Criteria:**

1. The ratio of external (unavoidable) noise to internally generated noise at the output of a receiver front end should be large.

2. The TPG should be reasonably flat over the passband.

- Channels are jointly optimized using GENESYS.
- Channel 1 & 2 are optimized to achieve maximum flatness.
- Channel 3 & 4 are optimized to get maximum TPG.
Results: Noise Dominance

“External noise dominance” in VHF-High and 220 MHz bands

<table>
<thead>
<tr>
<th>Component</th>
<th>Channel 1</th>
<th>Channel 2</th>
<th>Channel 3</th>
<th>Channel 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>L1 (nH)</td>
<td>377.1</td>
<td>290.6</td>
<td>1355.4</td>
<td>1322.5</td>
</tr>
<tr>
<td>C1 (pF)</td>
<td>2.8</td>
<td>6.9</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>L2 (nH)</td>
<td>9.7</td>
<td>7.6</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>C2 (pF)</td>
<td>108.7</td>
<td>1361.1</td>
<td>391.4</td>
<td>389.4</td>
</tr>
<tr>
<td>L3 (nH)</td>
<td>561.6</td>
<td>402.9</td>
<td>2021.9</td>
<td>2101.2</td>
</tr>
<tr>
<td>C3 (pF)</td>
<td>1.9</td>
<td>2.6</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>L4 (nH)</td>
<td>9.7</td>
<td>8.3</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>C4 (pF)</td>
<td>108.7</td>
<td>125.1</td>
<td>391.4</td>
<td>437.5</td>
</tr>
<tr>
<td>L5 (nH)</td>
<td>377.1</td>
<td>207.2</td>
<td>1357.4</td>
<td>1301.4</td>
</tr>
<tr>
<td>C5 (pF)</td>
<td>2.8</td>
<td>5.1</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Multiplexer in the Prototype

Impedance of actual antenna used (ANT-433-CW)

Multiplexer using ANT-433-CW

$5 Antenna from Digikey
RF Front End Board

VT RF Front End Board

- RF Multiplexer to interface with Antenna
- Low Noise Amplifier
- Additional Filters
- Variable Attenuators to control gain
- 4 Layer PCB
- About $200 in parts to implement
Digital Signal Processing

VT ADC / DAC / LO Synthesizer Board
- ADC/DAC: 130 mA @ 9V, running 4 MSPS
- Implement on a 4-layer PCB
- ADC ~ $21 (1k), DAC ~ $10 (1k)

EP2S60 Stratix II DSP development board
- Altera Stratix II FPGA
- Audio CODEC
- Firmware is written in Verilog HDL
- This FPGA is extremely overkill for this application

Multiband/Multimode Radio
Hasan / Ellingson – October 28, 2008
User Interface & Audio Board

Gumstix LCD pack
- 600 MHz Intel PXA27X Processor
- Samsung touchscreen LCD
- X-Window Operating System in 2GB SD card

Audio Board
- Connect standard handheld Mic & Spkr
- Audio amplifiers for MIC & Speaker
- Supplies PTT signals to FPGA

Multiband/Multimode Radio
Hasan / Ellingson – October 28, 2008
Prototype

138-174 MHz
220-222 MHz
406-512 MHz
764-900 MHz

Motorola RFIC Ver. 4
4 MSPS baseband ADC/DAC

No µP; Instead completely implemented in FPGA

Status (10/23/08)
RF Mux: Works
RFIC Board: Works
ADC/DAC: Works
Baseband: Analog FM Only
CODEC: Works
PTT: Works

Multiband/Multimode Radio
Hasan / Ellingson – October 28, 2008
Summary Remarks

- RF multiplexer optimized to antenna impedance with external noise dominance constraint, allows good performance in multiple bands

- **Principal advantage over reconfigurable matching techniques:**
  Simultaneous access to multiple bands

- Good result with 20 cm 5 mm rod antenna, but less good performance with commercial (433 MHz) antenna
  - Co-design of antenna and multiplexer may be advantageous

- Performance of RFIC-based design is still a bit short of public safety selectivity and dynamic range requirements

- **Challenges:**
  - Requires amplifier with a little better NF than commonly used
  - Realizing small filter footprint
  - Building a good user interface to control the whole radio
Thanks!

Acknowledgements:
Motorola: G. Cafaro, B. Stengle, N. Correal
Mahmud Harun (student)
Rithirong Thandee (student)
Qian Liu (Student)

Project Web Site:
http://www.ece.vt.edu/swe/chamrad/

Contact:
S.M. Hasan: hasan@vt.edu
S.W. Ellingson: ellingson@vt.edu

U.S. Dept. of Justice
National Institute of Justice
Grant 2005-IJ-CX-K018