Multiband Antenna-Receiver Integration using an RF Multiplexer with Sensitivity-Constrained Design

S.M. Hasan and S. W. Ellingson

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

July 10, 2008
Motivation (1/2)

For Multiband Multimode Radios (MMR)s

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

- **Direct Conversion Design**-
  Low Cost/ Small Size/ Low Power/ No IR Filter

**Cons:** I/Q imbalance, 1/f noise, 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

Direct Conversion CMOS RFIC

- RF Multiplexer

RFIC from Motorola Research Lab

- 5 RX Paths, 3 TX Paths
- 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

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

**Ratio of external noise to front end noise,**

$$\gamma = \eta (1 - |\Gamma|^2) \frac{T_{ext}}{T_{FE}}$$

**Reflection co-efficient,**

$$\Gamma = \frac{Z_{in} - Z_{ant}}{Z_{in} + Z_{ant}}$$
Antenna Model (1/2)

Thevenin model of antenna

TTG* model of antenna impedance

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


\[ C_1 = \frac{12.674h}{\log(2h/a) - 0.7245} \text{ pF} \]
\[ C_2 = 2h \left\{ \frac{0.89075}{[\log(2h/a)]^{0.8006} - 0.861} - 0.02541 \right\} \text{ pF} \]
\[ L = 0.2h[[1.4813 \log(2h/a)]^{1.012} - 0.6188] \text{ uH} \]
\[ R = 0.41288[\log(2h/a)]^2 + 3.70377(2h/a)^{-0.02389} - 3.63704 \text{ kOhm} \]

\[ h = \text{height} \]
\[ a = \text{radius} \]
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>Celestial$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-30</td>
<td>$3.81 \times 10^{25}$</td>
<td>$2.53 \times 10^{26}$</td>
<td>$8.54 \times 10^{26}$</td>
<td>$2.30 \times 10^{27}$</td>
<td>$1.07 \times 10^{23}$</td>
</tr>
<tr>
<td>b</td>
<td>2.86</td>
<td>2.77</td>
<td>2.77</td>
<td>2.77</td>
<td>2.52</td>
</tr>
<tr>
<td>30-100</td>
<td></td>
<td>$2.53 \times 10^{26}$</td>
<td>$8.54 \times 10^{26}$</td>
<td>$2.30 \times 10^{27}$</td>
<td>$1.07 \times 10^{23}$</td>
</tr>
<tr>
<td>b</td>
<td></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>$2.53 \times 10^{26}$</td>
<td>$8.54 \times 10^{26}$</td>
<td>$2.30 \times 10^{27}$</td>
<td>$1.07 \times 10^{23}$</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td>2.77</td>
<td>2.77</td>
<td>2.77</td>
<td>2.52</td>
</tr>
<tr>
<td>130-250</td>
<td></td>
<td>$2.53 \times 10^{26}$</td>
<td>$8.54 \times 10^{26}$</td>
<td>$7.46 \times 10^{14}$</td>
<td>$1.07 \times 10^{23}$</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td>2.77</td>
<td>2.77</td>
<td>1.23</td>
<td>2.52</td>
</tr>
<tr>
<td>250-900</td>
<td></td>
<td></td>
<td></td>
<td>$7.46 \times 10^{14}$</td>
<td>$1.07 \times 10^{23}$</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td></td>
<td></td>
<td>1.23</td>
<td>2.52</td>
</tr>
<tr>
<td>900-3000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1.07 \times 10^{23}$</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.52</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>5.3 dB$^2$</td>
<td>5.3 dB</td>
<td>4.5 dB</td>
<td>6.6 dB$^3$</td>
<td>-$^4$</td>
</tr>
</tbody>
</table>

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

Mean noise temperature, $T = af^{-b}$ [K]

External Noise limits receiver’s sensitivity if -

$T_{ext} > T_{FE}$
This is the noise figure required of an amplifier attached to an antenna if the output is 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

RF Multiplexer
**Multiplexer Architecture**

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.

![5th order Chebyshev bandpass topology](image)
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

Component Values

<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>1357.4</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>138.1</td>
<td>391.4</td>
<td>389.4</td>
</tr>
<tr>
<td>L3 (nH)</td>
<td>561.6</td>
<td>402.9</td>
<td>2041.9</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>0.4</td>
</tr>
</tbody>
</table>

Component Values

RF Multiplexer
Prototype MMR

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

Off-the-shelf antenna

Touchscreen

Audio

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

Real $Z_{\text{ant}}$

Imag $Z_{\text{ant}}$

Multiplexer using ANT-433-CW

Three board stack integrates antenna, RF Mux, transceiver RFIC, ADC / DAC, ref. freq. synthesizer

Battery underneath

Ethernet

Altera EP2S60 FPGA Board

RF Multiplexer
Summary Remarks

- **Key Idea:** 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

- **Challenges:**
  - Requires amplifiers with little better NF than commonly used
  - Realizing small filter footprint

**Project Website:**
http://www.ece.vt.edu/swe/chamrad/

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