Design and Implementation of Backscatter Links with Software Defined Radio for Wireless Sensor Network Applications

John Kimionis
Thesis Supervisor: Aggelos Bletsas
Telecom Lab, ECE Department, Technical University of Crete

November 22, 2011
Outline

Introduction / Backscatter Sensor Networks

Semi-passive Backscatter Tag Design

SDR Reader Design and Backscatter Links

Conclusion, Ongoing and Future Work
Outline

Introduction / Backscatter Sensor Networks

Semi-passive Backscatter Tag Design

SDR Reader Design and Backscatter Links

Conclusion, Ongoing and Future Work
Basic Idea: Sensing for Precision Agriculture

Micro-climate monitoring for every plant!

- Ultra low-cost.
- Ultra low-power.
- Ultra high network density.

No existing technology for all above. Existing technologies (e.g. ZigBee) can be cost-effective(?) but not energy-efficient.
Approach to a new form of Sensor Networks

- Complexity Shift.
- “Dumb” transmitters Intelligent Receiver/Reader.
- Semi-passive backscatter sensors.
- Backscatter communication for low-cost / low-power.
Backscatter: Transmission without Radiation

- Reader transmits carrier.
- Carrier induced on tag’s antenna.
- Carrier with altered phase or/and amplitude scattered back.
- Reader detects changes and decodes data.
- Tag may rectify RF carrier power or carry battery.
- Minimal RF front-end ⇒ Low-cost and low-energy!
Big Picture: Fields with Backscatter Sensors

RF tags with different ranges:
- Short range: Passive tags (rectify RF).
- Mid range: Semi-passive tags (battery-assisted).
- Long range: Active tags (classic radio).

A greenhouse or field can be full of semi-passive sensors, demanding little amounts of battery energy.
Prior Art Examples


Experimental Setup

- Signal Generator transmitting carrier at 867MHz, 30dBm output power, with a 3dBi omnidirectional antenna.
- Spectrum Analyzer and Software Defined Radio tuned at 867MHz, receiving bandwidth of 1 MHz.
- Custom semi-passive tags.
Outline

Introduction / Backscatter Sensor Networks

Semi-passive Backscatter Tag Design

SDR Reader Design and Backscatter Links

Conclusion, Ongoing and Future Work
Semi-passive Tag

- Full custom, designed and built in Telecom Lab, ECE, TUC.
- SiLabs C8051F320 low-power MCU.
- RF transistor driving omni antenna.
- 3V coin battery holder and sensor connectors.
Tag Hardware Design.

- Full custom PCB designed using CadSoft Eagle free CAD.
- EMI design rules.
- Low-cost components.
- Total board cost < $10.
Sensing.


- Ultra low-power sensor circuitry (max 300µA current consumption).
- Low-cost components and fabrication (5x cheaper than commercial products).
- High measurement accuracy.

Use of cheap sensors made of plaster, too! ($0.01)
Semi-passive Tag RF Part.

- Antenna with nominal impedance $Z_a$.
- Antenna load controlled by RF transistor on/off states.
- System reflection coefficient is

$$\Gamma_i = \frac{Z_i - Z_a^*}{Z_i + Z_a^*}, \quad i = 1, 2.$$

- Maximization of $|\Gamma_1 - \Gamma_2|$ required to minimize BER.

(Bletsas et al, *IEEE MTT 2010*)
Transistor Measurement and Selection.

- Several transistors measured.
- Measure $\Gamma_1, \Gamma_2$ with 1-port Network Analyzer.
- Average measurements and calculate $|\Gamma_1 - \Gamma_2|$ on PC.
Transistor Measurement Results.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>CEL</th>
<th>NXP</th>
<th>Agilent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>NE68033-A</td>
<td>BFS17NTA</td>
<td>AT-32033</td>
</tr>
<tr>
<td>$</td>
<td>\Gamma_1 - \Gamma_2</td>
<td></td>
<td>1.2084</td>
</tr>
<tr>
<td>Transition Freq.</td>
<td>10GHz</td>
<td>3.2GHz</td>
<td>10GHz</td>
</tr>
<tr>
<td>Power Dissipation</td>
<td>200mW</td>
<td>330mW</td>
<td>200mW</td>
</tr>
</tbody>
</table>

- NXP BFS17NTA is the winner.
- $|\Gamma_1 - \Gamma_2| = 1.9991 \approx 2$ = optimum!
- Agilent AT-32033 good performance with lower consumption.
Outline

Introduction / Backscatter Sensor Networks

Semi-passive Backscatter Tag Design

SDR Reader Design and Backscatter Links

Conclusion, Ongoing and Future Work
Software Defined Reader

- Ettus Research USRP1 with RFX900 UHF front end.
- Adjustable sampling rate, up to 64MSamples/sec.
- USB connection to host PC.

Software interfacing with GNU Radio for adjusting carrier frequency, ADC sampling rate, gain, etc. Custom pipe to MATLAB for signal processing.
Signal Model

- Simple channel model.
- The (noiseless) received signal at the reader is

\[
y_{nl}(t) = [ABe^{-j\Delta \phi} + ACE^{-jc} SDe^{-jd} x(t)] e^{-j2\pi \Delta F t} \\
= Ae^{-j2\pi \Delta F t - j\Delta \phi} [B + CSDe^{-j\phi_0} x(t)],
\]

where \( \Delta F \) is the carrier frequency offset between the signal generator and the SDR.
With AWGN channels and no CFO, the received signal is

$$y_{AWGN}(t) = A \left[ 1 + S \times (t) \right] + n(t), \quad n(t) \sim \mathcal{CN}(0, \sigma_n^2).$$

Tag’s information modulated on top of carrier’s DC!
SNR of tag’s signal depends on carrier’s amplitude!

$$\text{SNR} \propto |y_{nl}(t)|^2 \propto A^2.$$ 

By lowering carrier power by 6dB, the tag’s amplitude is halved (i.e. 6dB power decrease).
Digital Signal Processing performed in MATLAB

- Designed receiver capable of processing On-Off Keying and Frequency Shift Keying.
Backscatter Receiver (cont.)

- Low bitrate communication.
- Bit-by-bit varying channel.
- No channel/CFO estimation in practical backscatter.
- Frequency offset compensation by complex baseband signal’s magnitude observation.
  - Magnitude follows a Rice distribution.
  - For large carrier-to-noise ratio values, the magnitude’s observation can be approximated with a Gaussian distribution.
- Pulse-matched filtering for OOK.
- Frequency correlation for non-coherent FSK.
- Sampling after time sync via preamble.
OOK Modulation Scheme/FM0 Line Coding

- Modulation scheme similar to industry standard Gen2 RFID tags.
- ‘High’ level: $\Gamma_1$.
  ‘Low’ level: $\Gamma_2$.
- FM0 line coding.
- Bit-rate on the order of 100kbps.
- Advantage: Simple amplitude detection.
- Downside: Modulated information close to strong carrier, affected by clutter.
Fandelvice Modulation Scheme

- Bit ‘0’: switch transistor at $F_0$.
  Bit ‘1’: switch transistor at $F_1$.
- Bit-rate on the order of 10bps ⇒ higher SNR.
- Advantage: Narrow bandwidth subcarrier.
- Downside: Low bit-rate but high $F_0, F_1$ means higher Nyquist sampling ⇒ slower processing.
OOK and FSK BER Performance

OOK 3dB inferior to BPSK.

$$P_b^{OOK} = Q \left( \sqrt{\frac{\mathcal{E}_b}{N_0}} \right), \quad \mathcal{E}_b = \frac{b^2}{2} T$$

Non-coherent FSK 1–3dB inferior to coherent FSK and OOK.

$$P_b^{FSK, nc} \approx \frac{1}{2} e^{-\frac{\mathcal{E}_b}{2N_0}}, \quad \mathcal{E}_b = \frac{b^2}{2} T$$
Modulation Schemes Comparison (in terms of BER)

- OOK outperforms non-coherent FSK in terms of BER.
- Low-bitrate FSK demands more processing power than OOK.
Modulation Schemes Comparison (in terms of range)

One might be fooled by BER analysis and prefer OOK over FSK. But:

- Environment reflections and non-ideal RF electronics ⇒ clutter around carrier ⇒ noise floor elevated.
- OOK affected by clutter ⇒ SNR degradation ⇒ shorter range.

Real-case experimentation shows ‘hidden’ challenges!
Range Performance

- Field Test using Spectrum Analyzer.
- Observe subcarrier power level vs noise power level (threshold is 6dB SNR).
- Bistatic dislocated reader.

<table>
<thead>
<tr>
<th></th>
<th>$d_{gt}$</th>
<th>$d_{tr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator to Tag</td>
<td>0.1m</td>
<td>25m</td>
</tr>
<tr>
<td>distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tag to Receiver</td>
<td>&gt; 100m</td>
<td>25m</td>
</tr>
<tr>
<td>distance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tag bitrate / Generator TX power</td>
<td>10bps @ 30dBm</td>
<td>10bps @ 30dBm</td>
</tr>
</tbody>
</table>
With OOK, framed ALOHA schemes can be used (e.g. Generation 2 RFID Standard).

Collisions may occur ⇒ Bigger delay for interrogation of tags.

Memory assisted detection for FM0 tags can resolve collisions.


But tags require receive chain and sync ⇒ added complexity!
Multiple Access in Backscatter Networks - FDMA

- Frequency division multiplexing with FSK modulation.
- Collisions a-priori eliminated.
- Each sensor owns specific subcarriers.
- Odd harmonics should be avoided.
- Reader filters around each tag’s subcarrier.
- Low bitrate $\Rightarrow$ narrow spectrum $\Rightarrow$ dense network.
Outline

Introduction / Backscatter Sensor Networks

Semi-passive Backscatter Tag Design

SDR Reader Design and Backscatter Links

Conclusion, Ongoing and Future Work
Conclusion

- Low-cost, low-power tags.
- Custom, low-cost reader.
- Fully functional links.
- Environmental sensing possible through backscatter.
- Theory met application.
Scalability

- Backscatter cells like GSM cells.
- WSN backbone with Telecom Lab iCubes.
- WiFi and GPRS connectivity.
- Internet of Things.
Range Extension

- Exploit antenna’s structural mode ⇒ maximize backscattered carrier power.
  (Bletsas et al, *IEEE MTT 2010*)

- Carrier roundtrip path loss ⇒ low-SNR signals.
  Solution: Hybrid system. Employ many low-cost carrier generators and one reader.

- Challenge: Backscatter multihop?
Power-harvesting and MCU-less Sensors

- Renewable Energy Sources or RF power harvesting!
- Design of MCU-less backscatter sensor
  - Humidity sensing resonant circuit and RF transistor.
  - Analog FM spectrum. Detect FFT peak and translate to humidity value.
  - Challenge: Multiple access/FDM and selective sensor wakeup.
Questions?
Thank You!