A 96 Mbit/sec, 15.5 pJ/bit 16-QAM Modulator for UHF Backscatter Communication

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- Background
- QAM Backscatter
  - Backscatter Theory
  - Experimental Results
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Motivation

- RFID used for identifying objects
- Last year, localization was a key research area
- After knowing what object is in view, where it is, What else can it tell me?
- Increased data rates are needed to carry sensor or other information
- RFID used for identifying objects
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Conventional View of Sensor Data Links

- For traditional low-power devices and sensors, data uplink is costly and has driven low-power sensor research.

  “A significant fraction of sensor network research has addressed the problem of energy-efficiency, \textit{primarily by exploiting the fact that computation is many orders of magnitude less expensive than radio communication.} This computation vs. communication trade-off has had a tremendous influence both on algorithm design as well as on sensor network platform design.”


- We will challenge this assumption.
Summary of Conventional Links

- Typical wireless links are symmetric. Each node runs its own radio. (WiFi, Bluetooth, etc.)

*An AP has the same radio chip as a mobile device!*

- What benefits in terms of power and circuit complexity are gained by breaking this symmetry?
MBS Uplink versus Conventional Radios

<table>
<thead>
<tr>
<th>Technology</th>
<th>Frequency (MHz)</th>
<th>Data Rate (Mbit/s)</th>
<th>Peak Transmit Power (dBm)</th>
<th>Modulation Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b</td>
<td>2400</td>
<td>11</td>
<td>20</td>
<td>PSK-CCK</td>
</tr>
<tr>
<td>802.11a/802.11g</td>
<td>5200/2400</td>
<td>54</td>
<td>23</td>
<td>OFDM</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>2400</td>
<td>0.723</td>
<td>0</td>
<td>FSK</td>
</tr>
<tr>
<td>THIS WORK</td>
<td>915</td>
<td>96</td>
<td>–</td>
<td>QAM (MBS)</td>
</tr>
</tbody>
</table>

- In this work, we implement QAM over a UHF backscatter link to achieve a data transfer rate of 96 Mbit/s.
- Data rates are comparable to existing wireless protocols, but operate with a significant reduction in power cost.
- This makes high-bandwidth wireless data transfer possible for power constrained devices.

Prior work in QAM Backscatter

- Simulations of 4-PSK / 4-QAM over backscatter link along with preliminary results were shown at IEEE RFID 2010.
The scattering from a loaded antenna is well-known [Green 1963, Hansen 1989]

\[ E_{\text{scat}}(Z_L) = E_{\text{scat}}(Z^*_a) + \Gamma^*(Z_L) \frac{E_{\text{ant}}I^*_m}{I_{\text{ant}}} \]
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- **Antenna mode scattering** is dependent on the conjugate reflection coefficient.

\[ \Gamma^*(Z_L) = \frac{Z_a^* - Z_L}{Z_a + Z_L} \]

- Backscattering works by presenting a time-varying load impedance to the antenna causing changes in the scattered fields due to antenna-mode scattering.
Baseband Signal Model

- Three signals are received by the reader:
  - A. Environmental Clutter

\[ E_{rcv} = E_{env} + E'_{scat}(Z'^*_a) + \Gamma^* \frac{E'_{ant} I'^*_m}{I'_{ant}} + N \]
Three signals are received by the reader:

A. Environmental Clutter

B. Antenna Structural Scattering

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B. Antenna Structural Scattering
C. Antenna Mode Scattering

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Baseband Signal Model

- Three signals are received by the reader:
  - A. Environmental Clutter
  - B. Antenna Structural Scattering
  - C. Antenna Mode Scattering

- Changes in multipath translate received fields from the antenna.
- Changes in path length (separation distance) rotate and scale received fields from the antenna.

\[
E_{rcv} = E_{env} + E'_{scat}(Z^*_a) + \Gamma^* \frac{E'_{ant}I'_m}{I'_\text{ant}} + N
\]
16-QAM Modulator Design

1. The desired QAM constellation is drawn in the I/Q plane.
2. I/Q points are converted to reflection coefficients.
3. From reflection coefficients, impedances are calculated.

Designed around a 50 Ohm, 915 MHz antenna.
A 16-to-1 multiplexer (mux) is implemented using cascaded Analog Devices ADG904 SP4T RF switches.

Mux is controlled by 4 digital lines (representing bits in a symbol)
Each impedance represents an individual symbol.
Measured Impedances

Ideal and Measured $\Gamma^*$ Values

<table>
<thead>
<tr>
<th></th>
<th>Ideal $\Gamma^*$</th>
<th>Measured $\Gamma^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_1$</td>
<td>-0.15</td>
<td>-0.19 + j0.03</td>
</tr>
<tr>
<td>$Z_2$</td>
<td>-0.45</td>
<td>-0.48 + j0.03</td>
</tr>
<tr>
<td>$Z_3$</td>
<td>-0.15 + j0.3</td>
<td>-0.16 + j0.3</td>
</tr>
<tr>
<td>$Z_4$</td>
<td>-0.45 + j0.3</td>
<td>-0.46 + j0.29</td>
</tr>
<tr>
<td>$Z_5$</td>
<td>0.45</td>
<td>0.44 + j0.04</td>
</tr>
<tr>
<td>$Z_6$</td>
<td>0.15</td>
<td>0.15 + j0.02</td>
</tr>
<tr>
<td>$Z_7$</td>
<td>0.45 + j0.3</td>
<td>0.44 + j0.33</td>
</tr>
<tr>
<td>$Z_8$</td>
<td>0.15 + j0.3</td>
<td>0.15 + j0.29</td>
</tr>
<tr>
<td>$Z_9$</td>
<td>0.45 + j0.6</td>
<td>0.42 + j0.63</td>
</tr>
<tr>
<td>$Z_{10}$</td>
<td>0.15 + j0.6</td>
<td>0.09 + j0.6</td>
</tr>
<tr>
<td>$Z_{11}$</td>
<td>0.45 + j0.89</td>
<td>0.44 + j0.9</td>
</tr>
<tr>
<td>$Z_{12}$</td>
<td>0.15 + j0.89</td>
<td>0.18 + j0.89</td>
</tr>
<tr>
<td>$Z_{13}$</td>
<td>-0.15 + j0.6</td>
<td>-0.19 + j0.62</td>
</tr>
<tr>
<td>$Z_{14}$</td>
<td>-0.45 + j0.6</td>
<td>-0.41 + j0.59</td>
</tr>
<tr>
<td>$Z_{15}$</td>
<td>-0.15 + j0.89</td>
<td>-0.14 + j0.9</td>
</tr>
<tr>
<td>$Z_{16}$</td>
<td>-0.45 + j0.89</td>
<td>-0.41 + j0.94</td>
</tr>
</tbody>
</table>

Simulated EVM 868 MHz 2.96%
915 MHz 0%
950 MHz 2.09%

Measured EVM 915 MHz 3.62%

- Using a VNA, impedances were measured. Measured values show good agreement with predicted, ideal locations for $Z_a = 50 + j0$.
- Next, we performed a series of over-the-air tests to confirm that the scattered fields have the correct magnitude and phase.
Tag is placed 2.75 m away from a +23 dBm, 915 MHz RF source. The tag is transmitting 500,000 symbols/sec for 4-PAM and 500,000 symbols/sec for 4,16-QAM (1 Mbps, 2 Mbps respectively)
When transmitting at 96 Mbit/s modulator power consumption is 1.49 mW (15.5 pJ/bit) with an Error Vector Magnitude of 9.38%.

(Power measurement does not include data generation circuitry.)
- **Measurement setup:**
  - 1.24 m separation distance
  - 915 MHz carrier
  - 8 dBi linear patch Tx, Rc
  - +23 dBm output power
  - 8 dBi tag antenna

- **Results:**
  - 196,736 bits (48,184 symbols)
  - BER < 5.08 x 10^-6
  - EVM = 9.38%
  - 1.49 mW (15.5 pJ/bit)
A maximum operational distance of 17.01 m is predicted for a 96 Mbit/s data rate

Assumptions:

- Reader Sensitivity limited (return link limited)
- 1 bps/Hz spectral efficiency
- Measured receiver noise figure of 19 dB
- 12 dB Eb/No margin (for BER of $10^{-3}$)
- Differential RCS determined by minimum distance between any 2 points in the constellation.
Conclusions

- A semi-passive 16QAM backscatter modulator was designed and built.
- The tag transmits a continuous stream of bits at 96 Mbit/sec with a modulator DC power consumption of 1.49 mW (15.5 pJ/bit)
- QAM backscatter power consumption is 50x lower than idle WiFi chipset.

Future Work

1. Single-chip CMOS implementation
2. Adaptive Equalization on the Reader
DIE ID

16-QAM Modulator Implemented in CMOS
Thank you!