

Beyond Identification

Research Opportunities in
Passive Sensing, Computing, and Communication

Matt Reynolds
Department of Electrical and
Computer Engineering
Duke University



Overview

1. Passive RFID Today
2. What can we learn from Passive RFID?
3. WiSPs: Passive Sensing, Computing, and Actuation
4. Machine Perception with RFID
5. Research Challenges

RFID Today: “Identification Focused”

Access Control and Payment

- Passive, Proximity Technologies
 - Door entry
 - Contactless Smart Cards and Ticketing
 - Livestock Management

Automatic Tolling

- Long Range, Semi-Passive Transponders
 - EZ-Pass and Title 21 Tolling

Inventory Management

- Retail
 - Wal-Mart / Sam’s, Metro, Marks & Spencer
- Manufacturing and Industrial Sectors
 - Boeing

Technical challenges conquered...

- Tag ICs
 - Gen2 tag powerup thresholds approaching -20dBm
 - Robust signaling and anticollision protocols
- Inlays
 - Tremendously improved inlay designs
 - Near-field and far-field hybrid designs
- Readers
 - Single-chip reader RF ASICs
 - Sensitivity beyond -90dBm in-channel
 - Improved adjacent channel rejection
 - Improved self-jammer rejection
 - Early deployment of phased array antennas

... plenty of room to improve on these metrics ...

RFID in the Near Future

Access Control and Payment

- Proximity Technologies
 - Door entry
 - Contactless Smart Cards (MIFARE)
 - Livestock Management

Automatic Toll Payment

- EZ-Pass and Title 21 Tolling

Inventory Management

- Retail
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Wireless Sensing

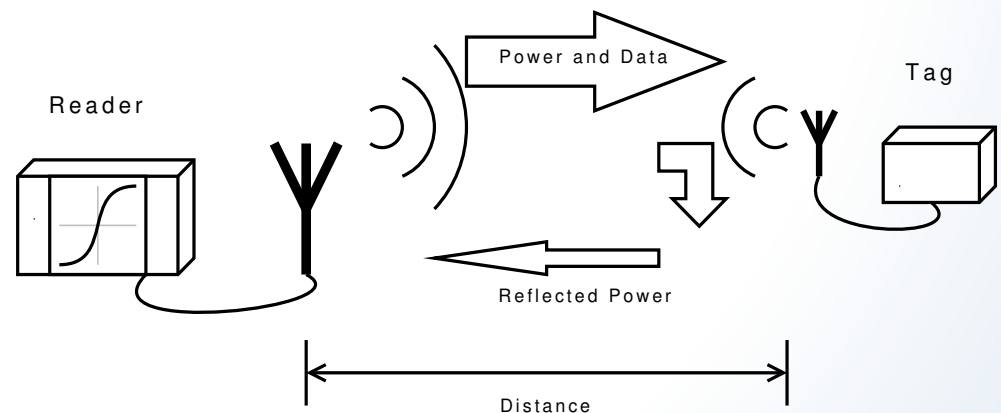
- Time, Temperature [Opas. et al., 2006]
- HF Biomedical [Fotop. and Flynn, 2006]
- UHF Pressure, Temp. [Sample, 2009]

Localization

- RTLS for Inventory
- Robotic Perception
 - Localization and Mapping [Burgard '05]
 - Pose Estimation [Deyle, Reynolds '08]
 - Object Manipulation [Deyle, Reynolds '09]

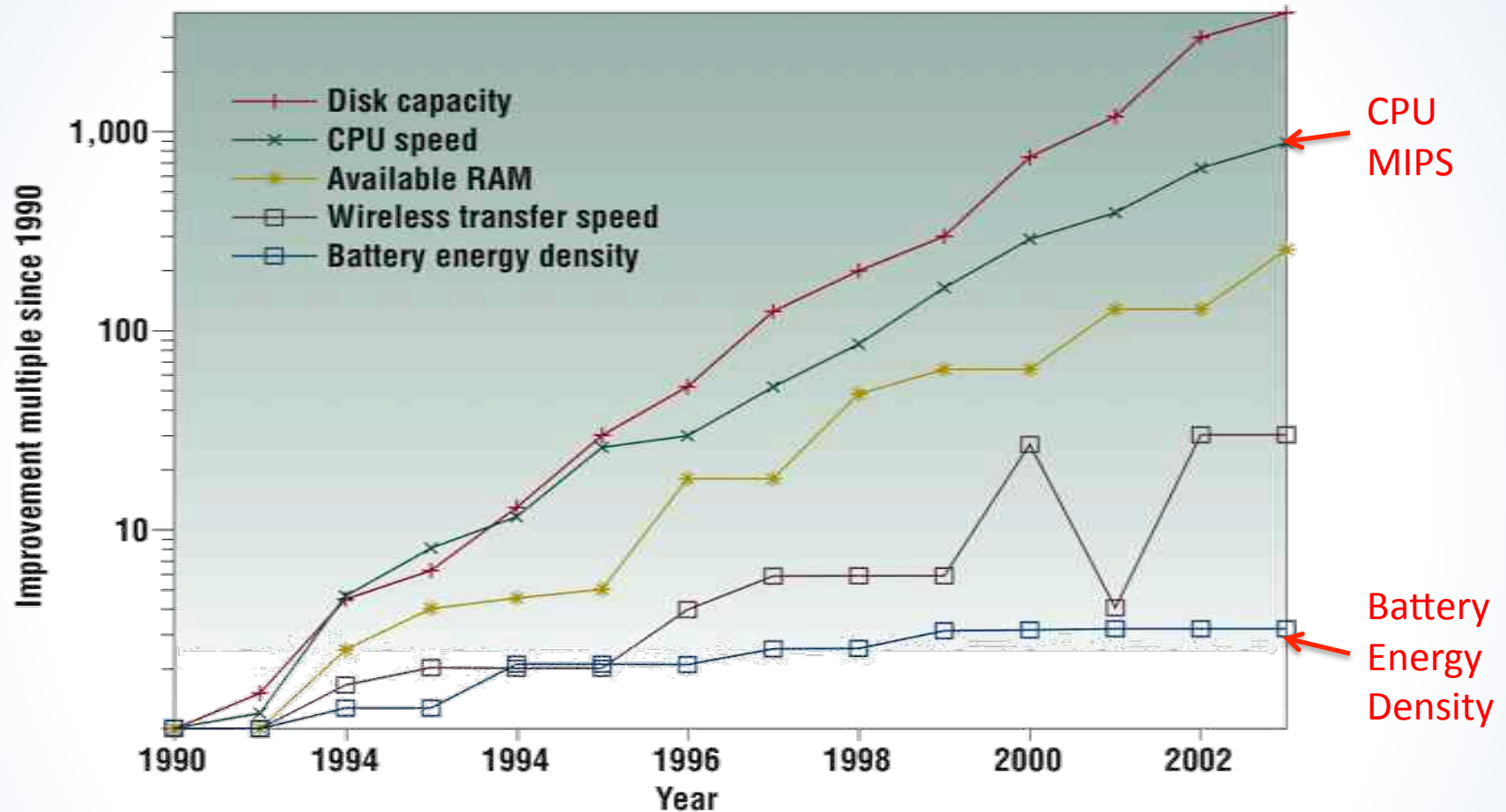
What can we learn from passive RFID?

- Passive RFID Technology Spans Electromagnetic Domains
 - LF (Near-Field / Inductive Coupling)
 - HF (Near-Field / Inductive Coupling)
 - UHF and Microwave (Far-Field / Backscatter)
- Focus on Microwatts, MIPS, and MEMS
 - Power Harvesting
 - μ W-Computing
 - μ W-Communication
 - Integrated Sensing



Passive RFID system

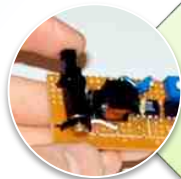
Microwatts and MIPS



Batteries Don't Follow Moore's Law.

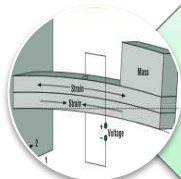
[Paradiso & Starner, 2005]

Power Harvesting Liberates Computing



Power Harvesting from Human Motion

- Battery-free RFID pushbutton, 15m range [Paradiso and Feldmeier, 2001]
- Biomedical sensors that live as long as their host



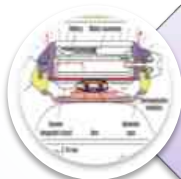
Vibrational Power Harvesting

- 400—600 μW (Avg.) [Roundy et al., 2005]
- Structural & Machine Health Monitoring
 - [Pisano et al., 2005]



Electromagnetic Power Harvesting

- Directed Beams (kW from space)
- Inductive coupling, resonant and non-resonant
- **WiSPs** [Sample et al, 2008]
- Passive DTV: 60 μW at 4 km [Sample and Smith, 2009]



Thermal Power Harvesting

- Seiko Thermic wristwatch ($\sim 2\mu\text{W}$)

Microwatts, MIPS, and MEMS

- New Forms of Sensing, Computing, and Actuation
 - Physical layer design + optimization
 - On-chip sensors and actuators
 - Tag localization
 - RFID aided perception
- Robotics + biomedical instrumentation applications



Dragonfly carrying UHF tag

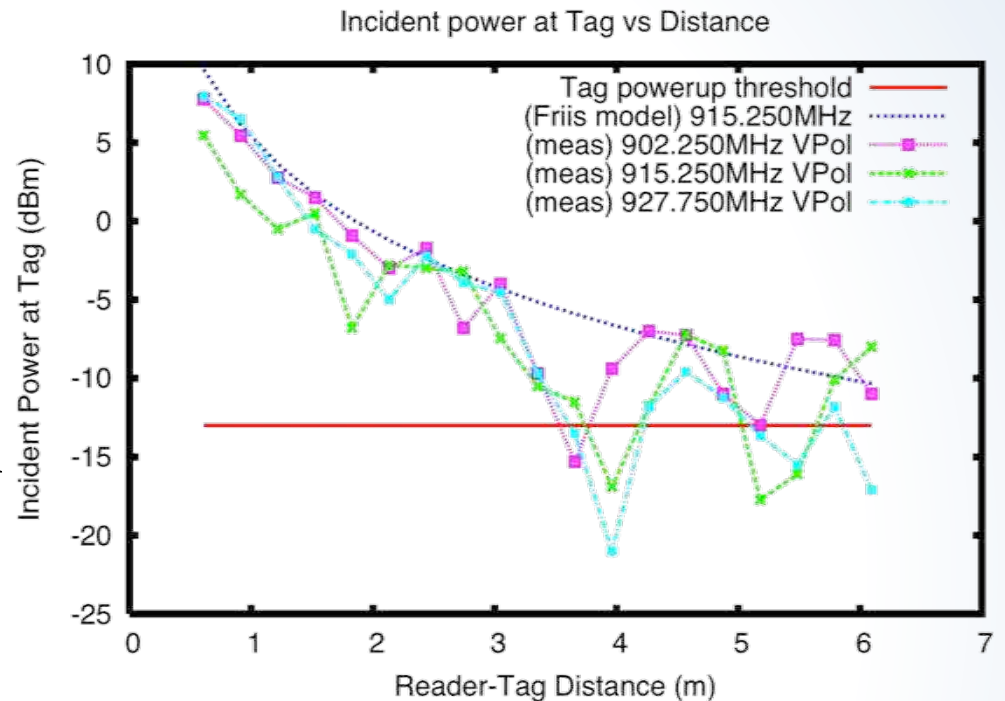


Tagged object localization and fetching

Power Available from 1W Incident RF

- Power Budget
 - 100 μW @ 6 m
 - 10 μW @ 20 m
- Real environments have lots of multipath
- Polarization diversity helps
- Need techniques for computing with unreliable power

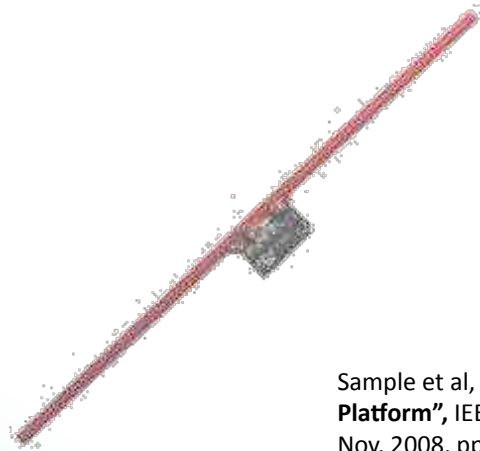
[K. Fu, W. Burlison, UMass Amherst]



$$P = \frac{G_{TX} G_{RX} \lambda^2}{4\pi d^2} \quad (\text{Only true in an anechoic chamber!})$$

What's a WiSP?

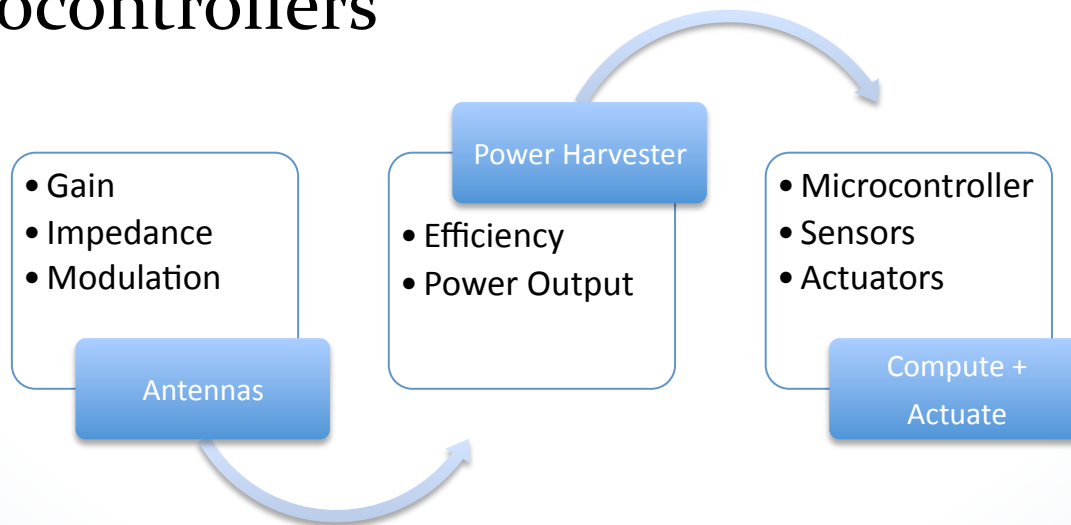
- **Wireless Identification and Sensing Platform** [Smith, 2005]
 - **Concept:** Passive RFID with a general purpose computing element
 - **Applications:** Sensing, crypto, protocol design, etc
 - **Inexpensive prototyping of new RFID concepts**



Sample et al, "Design of an RFID-Based Battery-Free Programmable Sensing Platform", IEEE Transactions on Instrumentation and Measurement, Vol. 57, No. 11, Nov. 2008, pp. 2608-2615.

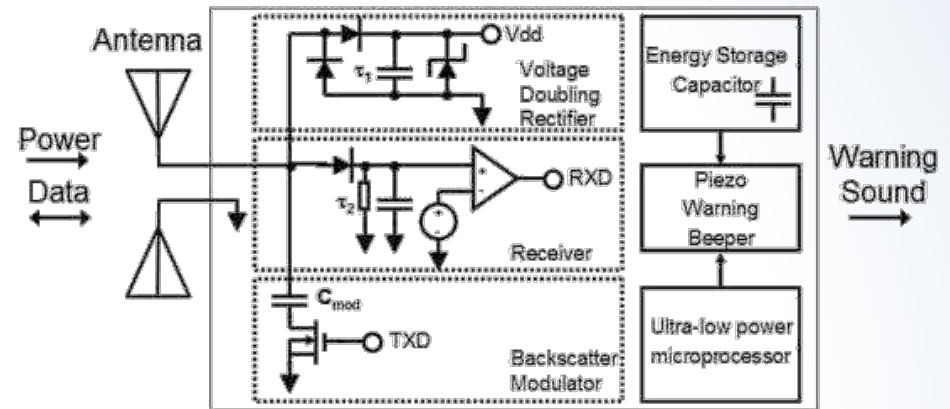
WiSPs at Duke

- Exploring the WISP design space
 - Novel Actuation Components
 - Piezoelectric speaker -> Piezo motors
 - Planar omnidirectional antennas
 - High data rate QAM backscatter modulation
 - Custom RFIC – WiSP companion chip for microcontrollers



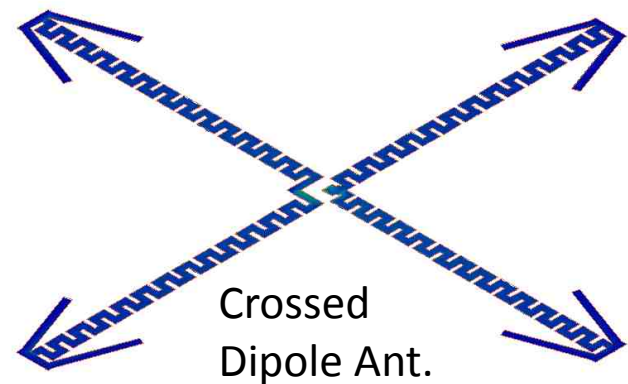
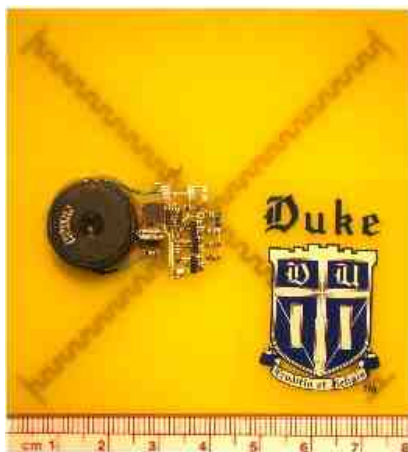
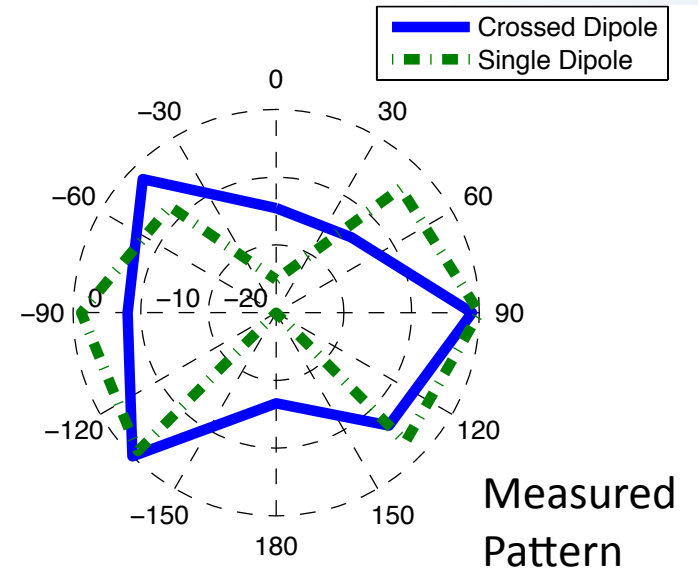
SmartHAT Safety Warning System

- WiSP + piezo actuator for construction site safety
- Reader mounted to heavy construction equipment
- WiSP in hard hat
- Passive operation allows unlimited lifetime- no batteries to fail



SmartHAT WiSP

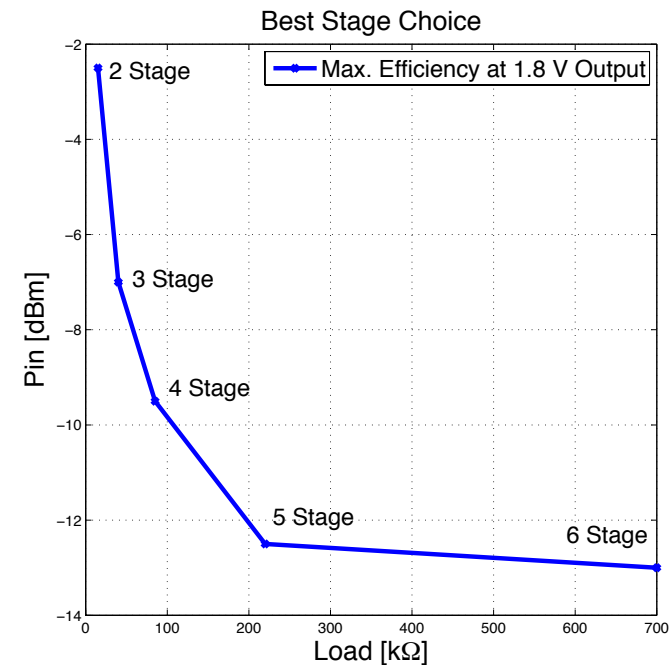
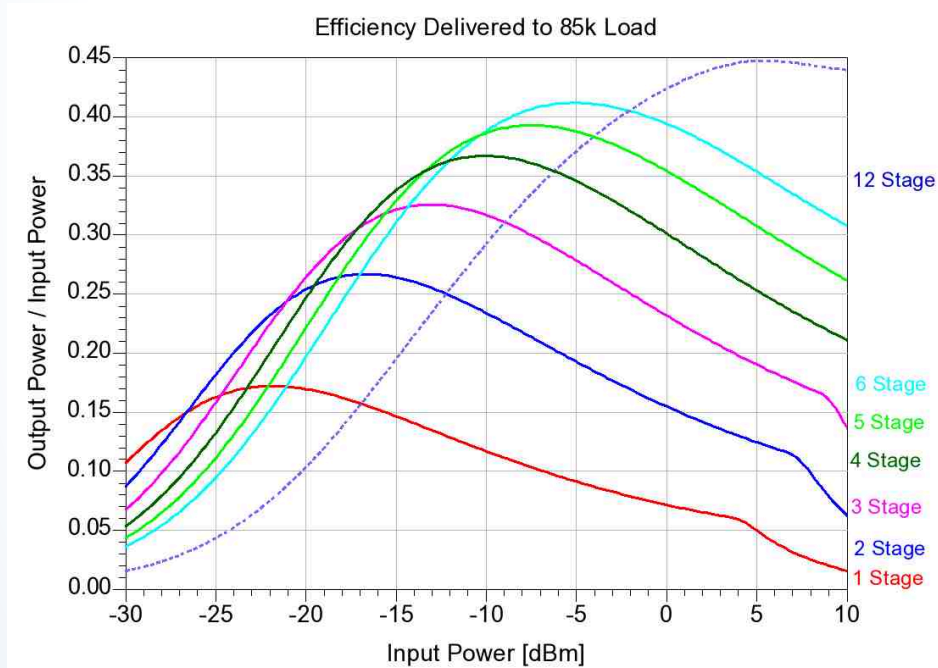
- Requirements
 - No Battery
 - Rugged, planar PCB antenna
 - 8cm x 8cm or smaller
 - Integrated matching network
 - Maximize bandwidth



[Thomas, Teizer, Reynolds, 2010]

Power Harvesters are Nonlinear

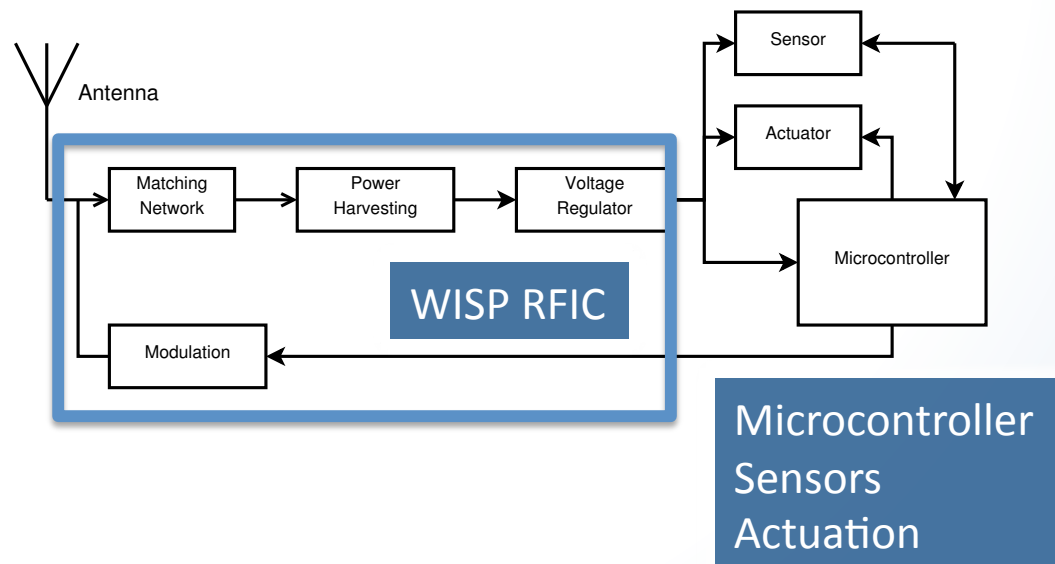
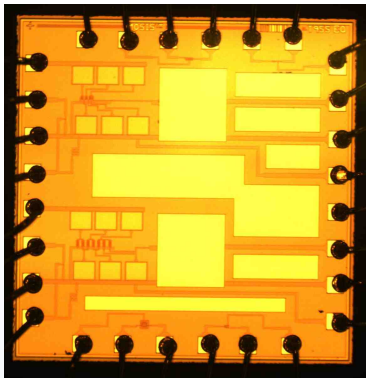
- Selecting operating point is critical in any RFID tag
- This is especially hard to do in a WiSP
 - Charging reservoir capacitor most of the time
 - Sleep current vs MCU current vs actuator current



ADS simulations confirmed by measurement at
3,4,5 stages

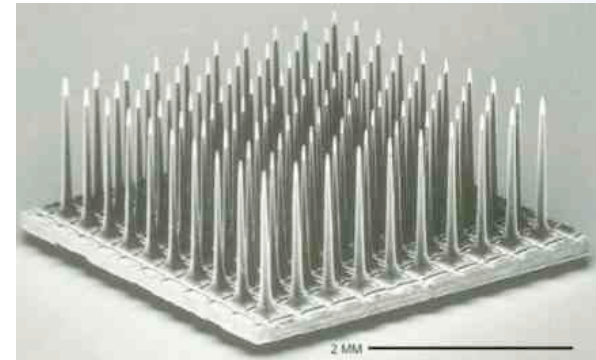
WiSP Companion RFIC

- MOSIS / AMI 0.5u-> 180nm Passive Analog Front End
- Support General Purpose Microcontroller: TI MSP430
 - Flexible protocol + sensor development
 - Extensive development tools
 - Partial Gen2 implementation available from Intel
- RFIC reduces WiSP complexity vs discrete AFE
- Include QAM backscatter modulation

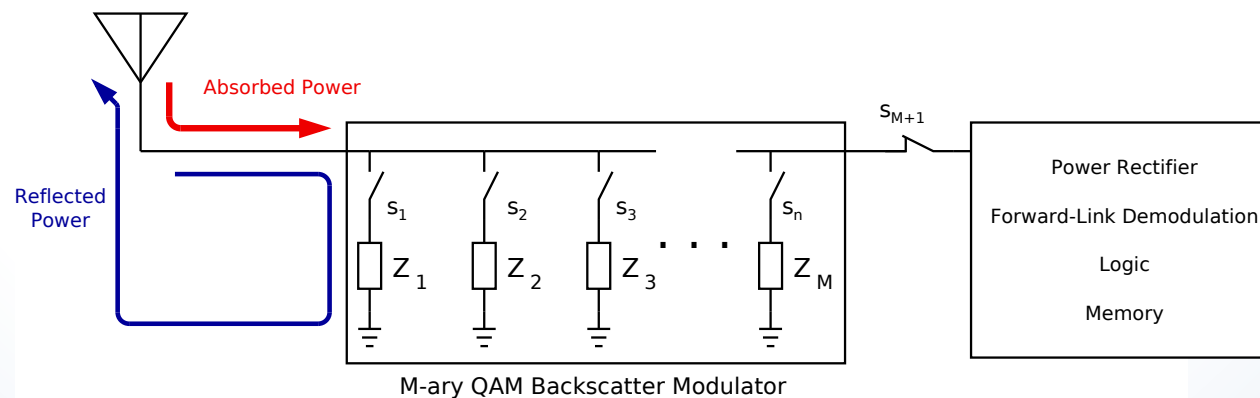


MBPS for μW

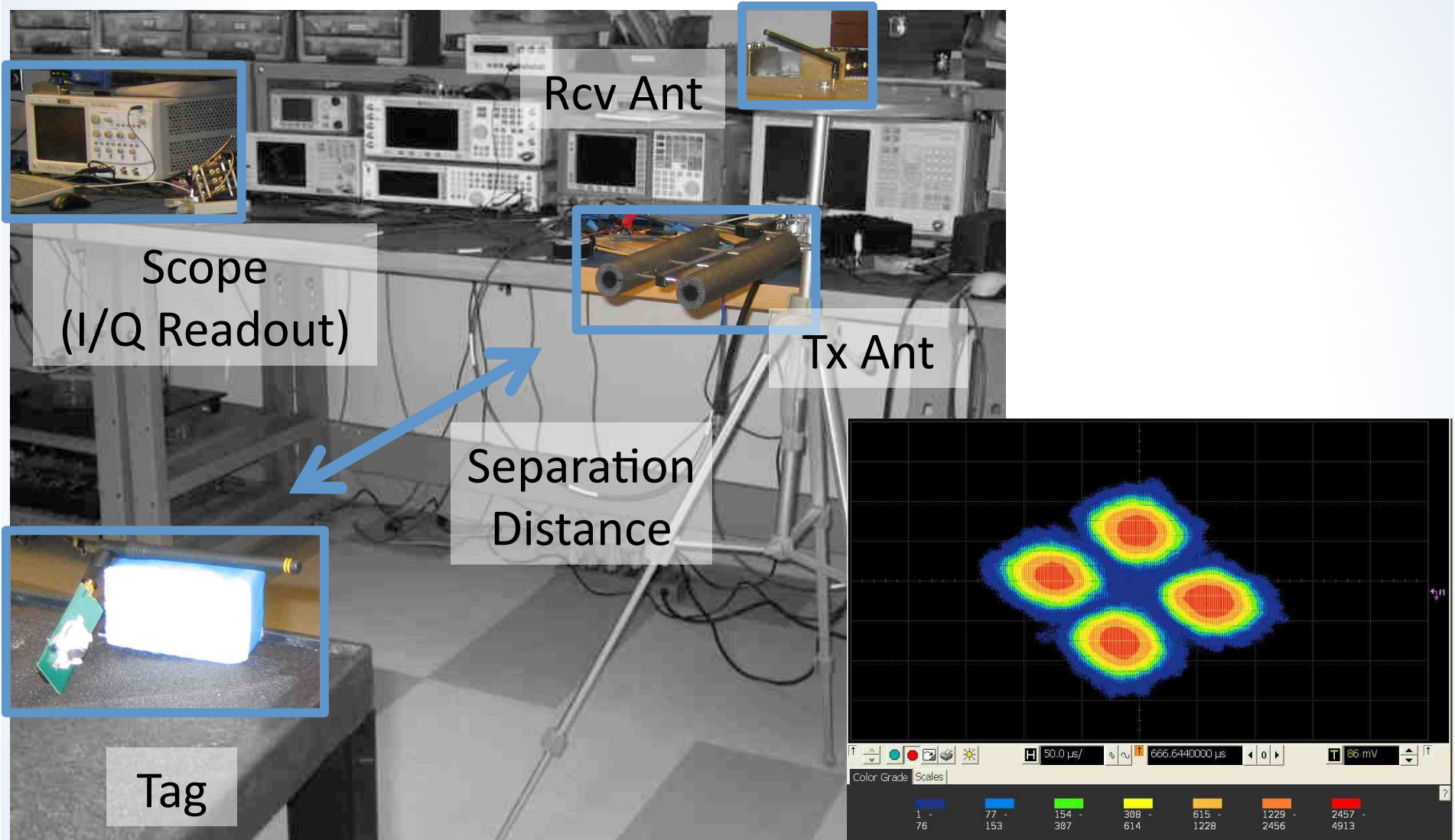
- Today's RFID backscatter links designed for small IDs or user memory blocks
 - Example: ISO18000-6c (Gen2)
 - ASK or PSK (2 states)
 - Up to 640kbps
- Neurotelemetry arrays require a much faster link ($>10\text{MBPS}$)
- Multi-state (QAM) backscatter sends multiple data bits per on-chip clock
- 2x to 4x power-bandwidth product improvement is possible with QAM backscatter!



Utah Array Fig: Harrison, R.R., "The Design of Integrated Circuits to Observe Brain Activity," *Proceedings of the IEEE*, vol.96, no.7, pp.1203-1216, July 2008



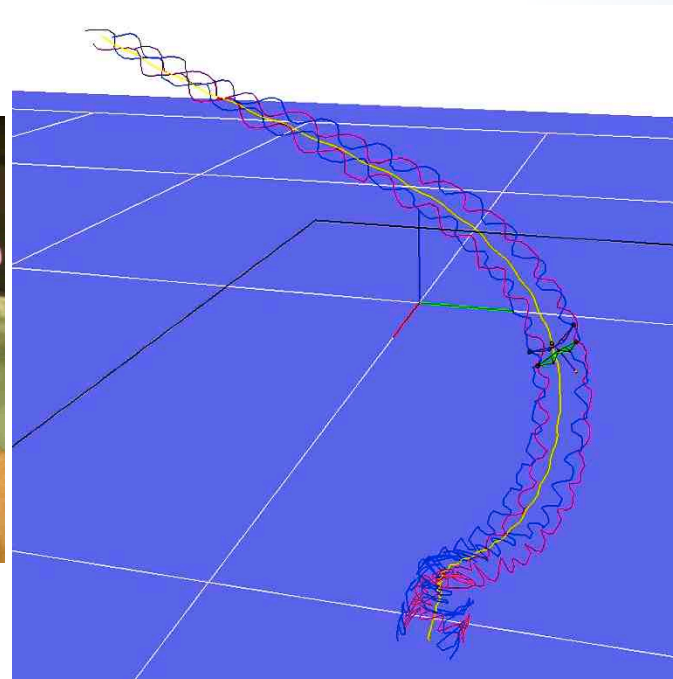
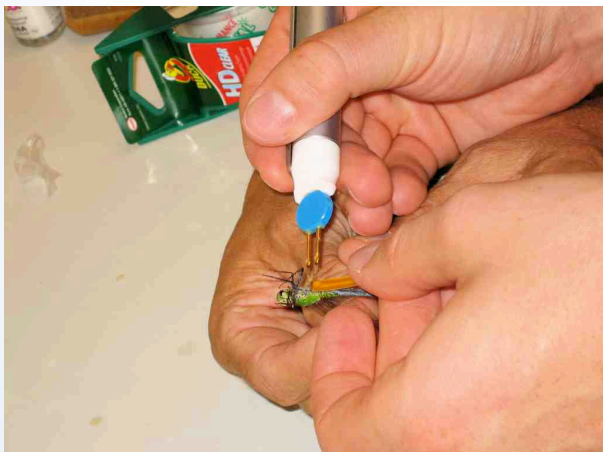
QAM Backscatter Over the Air



[Thomas, IEEE RFID 2010, Session 4B]

Labeling the World

- UHF RFID can label almost any object
 - Dragonfly mass: 100mg - 300mg depending on subspecies
 - Liftoff capacity: 1x - 3x body mass
 - Passive tag mass: 75mg including antenna
 - Attachment method: beeswax
 - Fuse ID from RFID with optical tracking



[Leonardo Lab, HHMI]

RFID for Machine Perception

- RFID offers “Sight Beyond Light”
 - UID for semantic labels of places and things
 - Essentially zero false-positive rate
 - Read around and through some obstacles
 - Distinct near-field and far-field behavior
 - Near-field: grasping objects
 - Far-field: sensing objects from across a room
- Challenges
 - Building semantic databases
 - Treating readers and tags as sensor systems
 - Taming multipath propagation
 - Fusing RFID with other sensors
 - Computational efficiency

Localization for Robotics

- Robots are moving platforms
 - Very challenging RTLS
 - Fuse RFID data with odometry, laser, vision sensors
- Incorporate motion model and sensor models into particle filter



[Deyle, Kemp, Reynolds, IROS 2008]

Particle Filter Framework

Particle filters are based on joint PDFs:

$$p(x_t | z_{1:t}, u_{1:t}, x_{1:t})$$

State
(range + bearing
in robot frame)

Sensor Readings
(RFID observations)

Control Updates
(Odometry)

Old States

Bayes' Rule + 1st Order Markov Assumption:

$$p(x_t | z_{1:t}, u_{1:t}, x_{1:t}) = \eta \cdot p(z_t | x_t) \cdot p(x_t | u_t, x_{t-1})$$

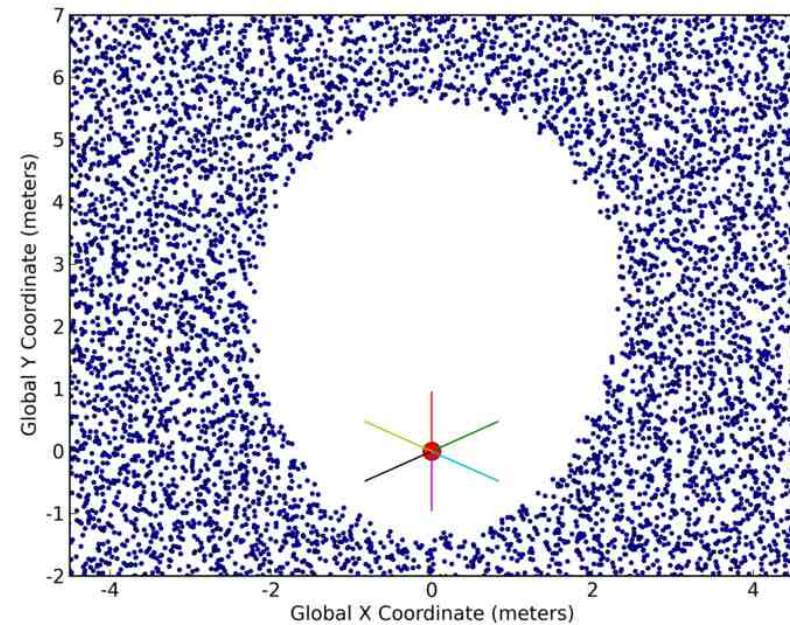
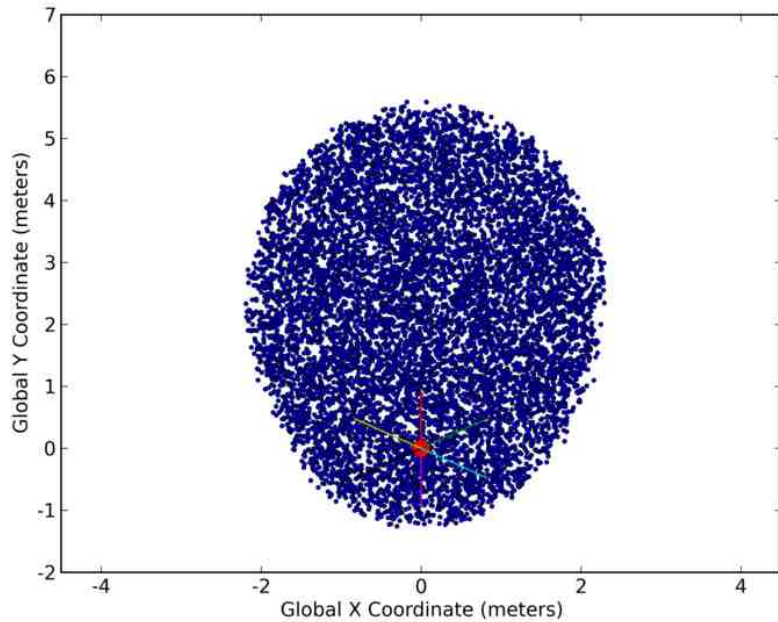
Sensor Model
(RFID signal
propagation model)

Robot Motion Model
(Odometry)

RFID Sensor Model

$$p(z_{t_i} = \text{Present} | x_t) = \begin{cases} 1.0 & \text{if } P_{tag}^{inc} \geq P_{tag}^{th} \\ 0.6 & \text{otherwise} \end{cases}$$

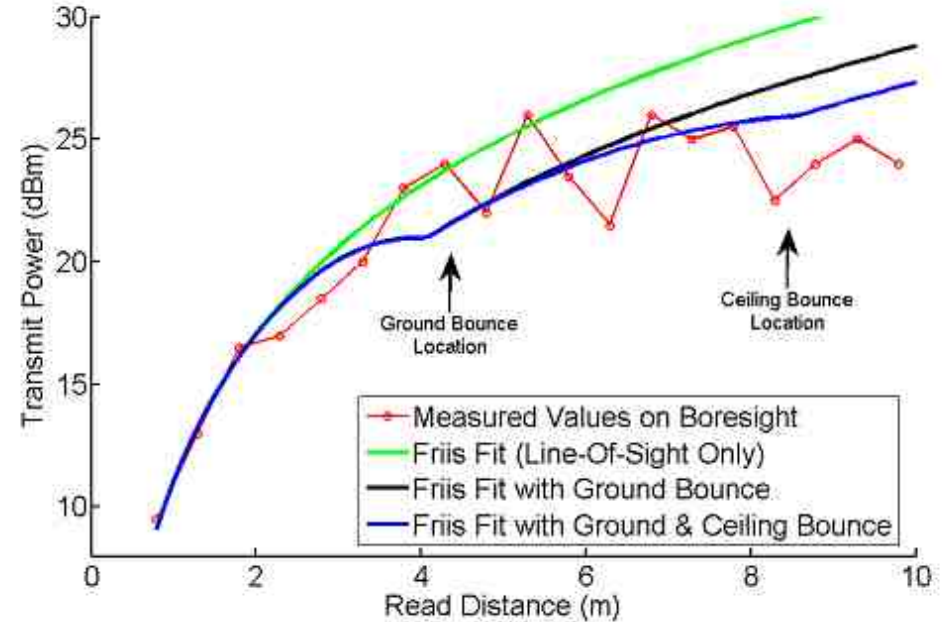
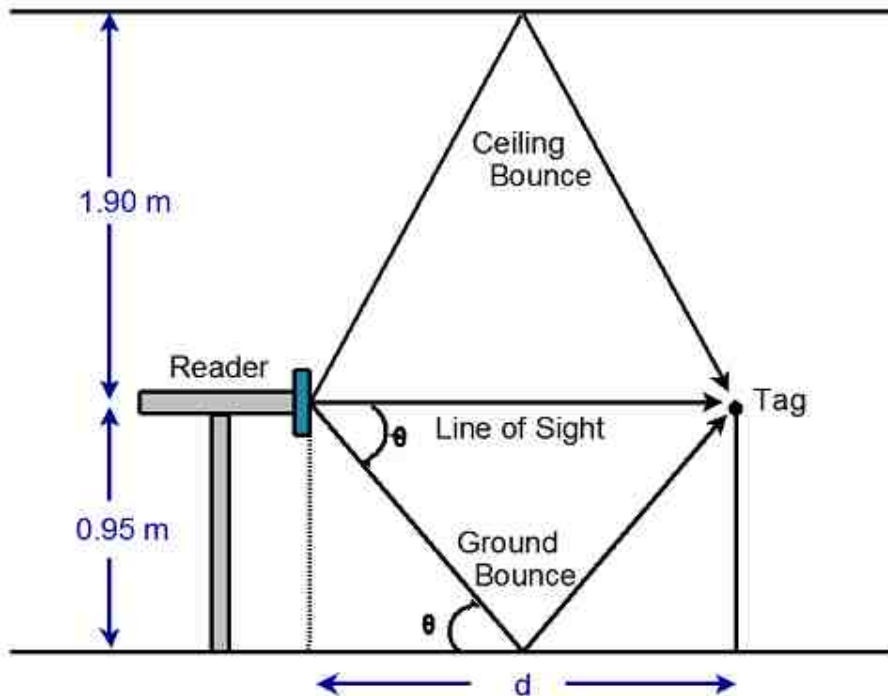
$$p(z_{t_i} = \text{Absent} | x_t) = \begin{cases} 1.0 & \text{if } P_{tag}^{inc} < P_{tag}^{th} \\ 0.6 & \text{otherwise} \end{cases}$$



Express probability of tag read using tag powerup threshold- Need antenna radiation pattern and propagation model with multipath.

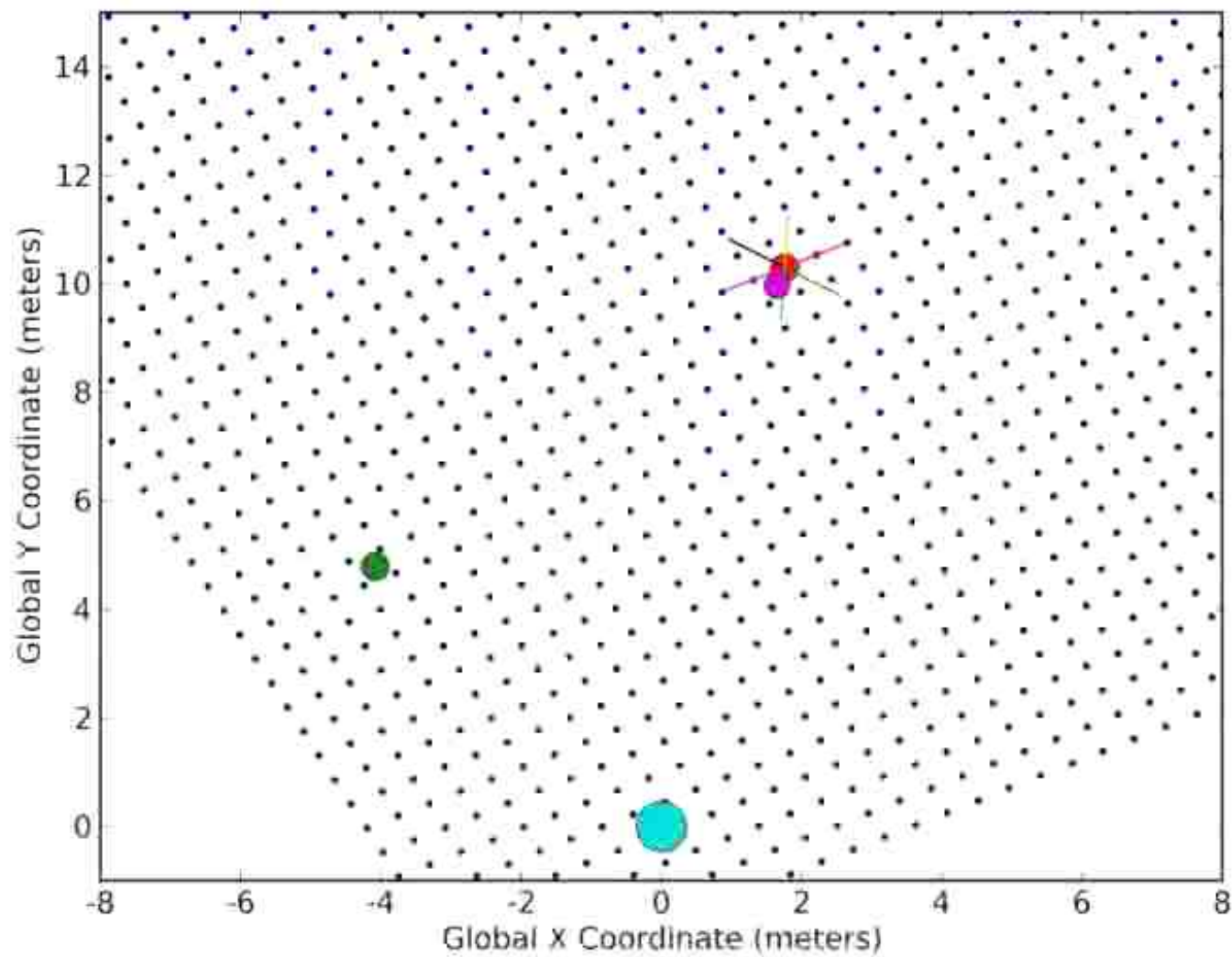
Multipath Model

$$P_{tag}^{inc} = P_{rdr} \cdot CL \cdot G_{tag} \cdot \left[\sum_{\text{all paths}} G_{rdr}(\theta) \cdot PL \right]$$



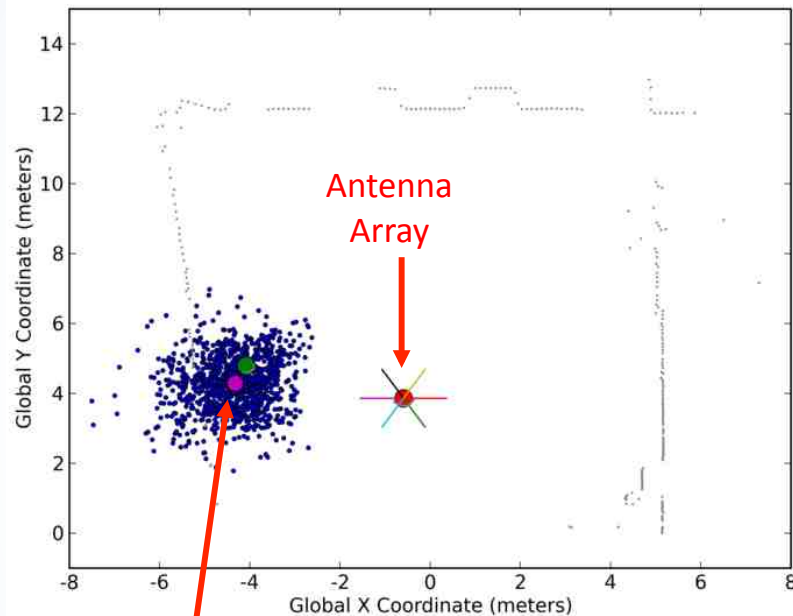
Ground bounce and ceiling bounce are dominant and allow model simplification for computational tractability.

Particle Filter during Robot Motion



Particle Filter Results

Tag tracking in 10m x 10m room



Estimated
Tag Locations

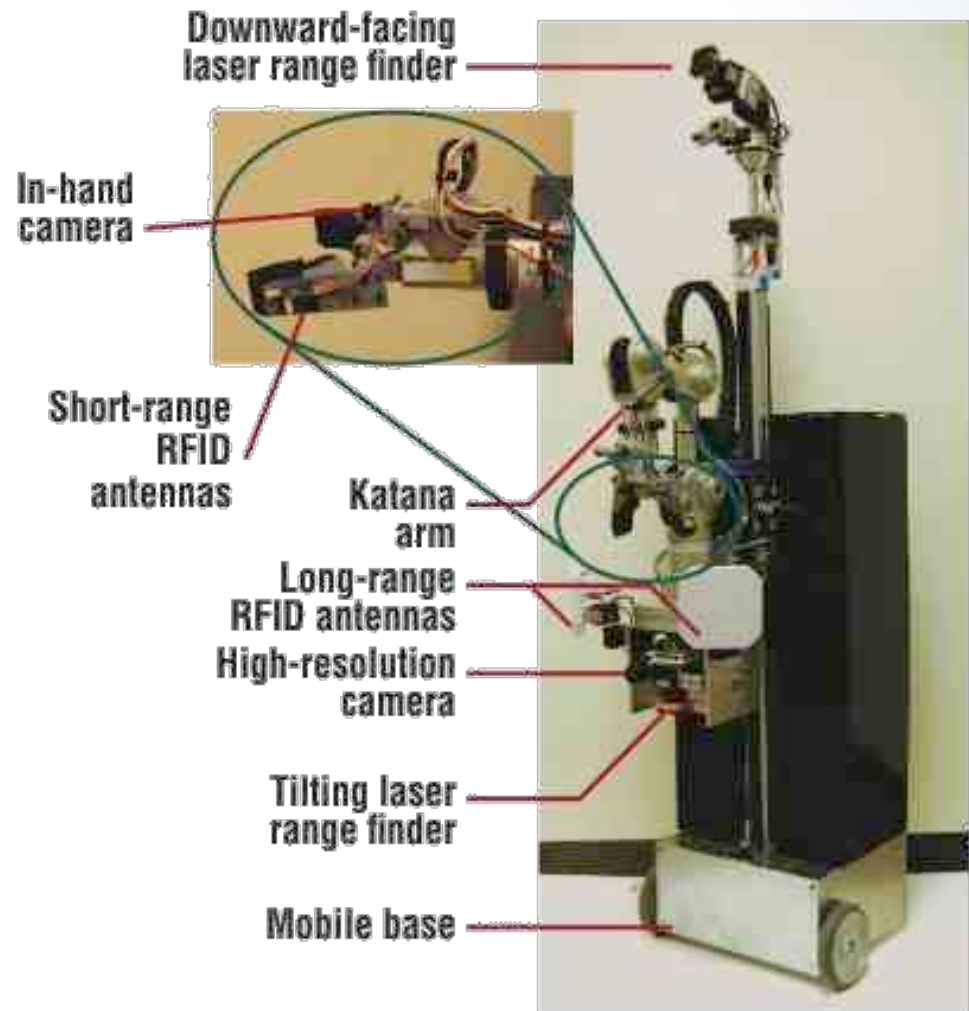
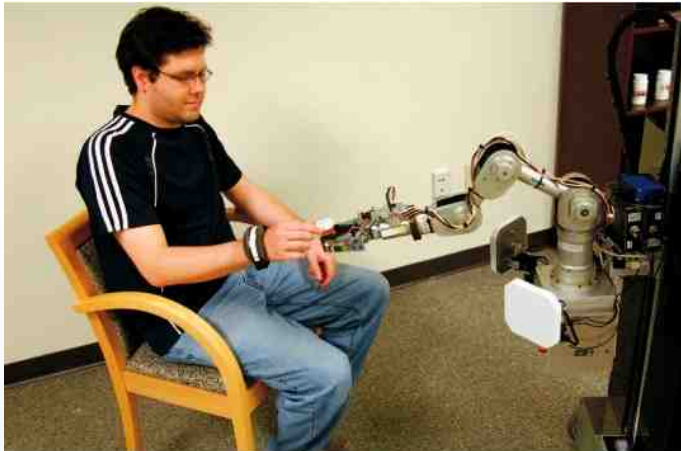
Range	Error Measures	Line-Of-Sight Only	With Ground & Ceiling Bounce
All d_{actual}	d_{error}	$\mu=0.71\text{m}$ $\sigma=0.45\text{m}$	$\mu=0.69\text{m}$ $\sigma=0.42\text{m}$
	d_{relative}	$\mu=16.2\%$ $\sigma=6.8\%$	$\mu=15.9\%$ $\sigma=6.6\%$
	θ_{error}	$\mu=6.11^\circ$ $\sigma=4.19^\circ$	$\mu=6.11^\circ$ $\sigma=4.19^\circ$
$d_{\text{actual}} \leq 4 \text{ m}$	d_{error}	$\mu=0.40\text{m}$ $\sigma=0.20\text{m}$	$\mu=0.41\text{m}$ $\sigma=0.21\text{m}$
	d_{relative}	$\mu=13.3\%$ $\sigma=6.0\%$	$\mu=13.6\%$ $\sigma=6.3\%$
	θ_{error}	$\mu=5.12^\circ$ $\sigma=3.62^\circ$	$\mu=5.08^\circ$ $\sigma=3.72^\circ$
$d_{\text{actual}} > 4 \text{ m}$	d_{error}	$\mu=1.05\text{m}$ $\sigma=0.39\text{m}$	$\mu=1.00\text{m}$ $\sigma=0.38\text{m}$
	d_{relative}	$\mu=19.3\%$ $\sigma=6.1\%$	$\mu=18.4\%$ $\sigma=6.1\%$
	θ_{error}	$\mu=7.17^\circ$ $\sigma=4.50^\circ$	$\mu=7.23^\circ$ $\sigma=4.38^\circ$

TABLE I
PARTICLE FILTER ACCURACY AFTER CONVERGENCE

Probabilistic UHF RFID tag pose estimation with multiple antennas and a multipath RF propagation model, Proc. IEEE Conf. Intelligent Robots and Systems (IROS '08), 2008.

El-E: An Assistive Robot using RFID

- Far-field antennas for tagged object localization across a room
- Near-field antennas in robot's hand for grasped object validation
- Mission: Manipulate Tagged Objects in a Semantically Appropriate Manner



PPS Tags: Physical, Perceptual, Semantic

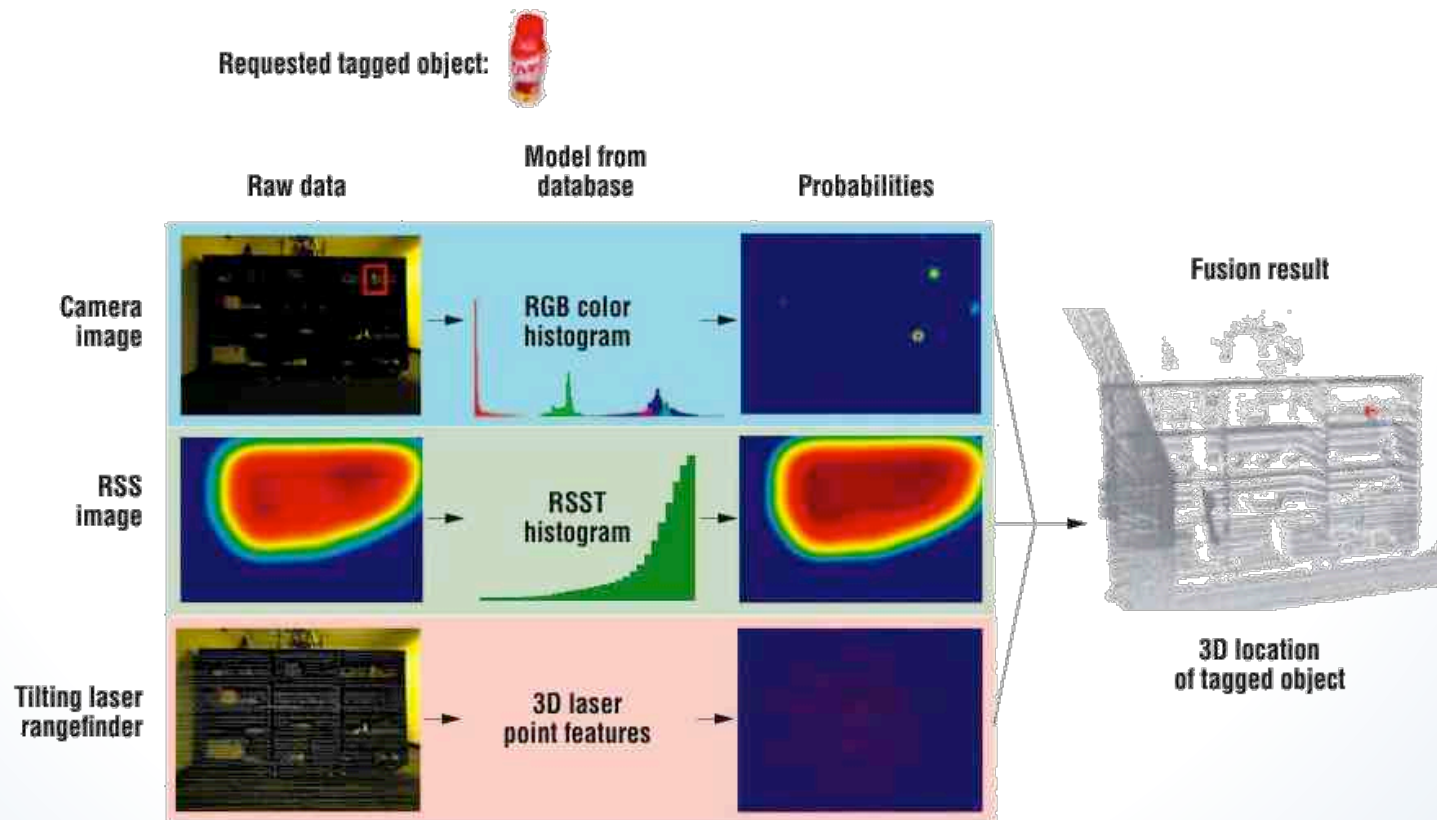
- Motivation: Service robots that perform tasks often done by service animals



```
'properties': {'type': 'ada light switch',  
              'name': 'A D A light switch 1',  
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              'change': 'overall brightness',  
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              'height': 1.22,  
              'on_plane': True,  
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              },  
  
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            'on': 'push_top'},  
  
'push_bottom': {'force_threshold': 3.0,  
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                'ele': {'gripper': 5}  
                },  
  
'push_top': {'force_threshold': 3.0,  
              'height_offset': 0.02,  
              'ele': {'gripper': 5}  
              }
```

El-E: The PPS Tag Pipeline

- User selects desired tagged object with a laser pointer
- El-E fuses camera, laser rangefinder, and RFID information to accomplish selected task



RFID Based Semantic Cues for El-E

- User designates tagged object with green laser pointer.
- El-E uses semantic database cued by tag UID to act on object

PPS-Tags: Physical, Perceptual, and Semantic Tags for Autonomous Mobile Manipulation

By Hai Nguyen, Travis Deyle,
Matt Reynolds, and Charles C. Kemp

Georgia Institute of Technology & Duke University

Where are the Research Challenges?

Access Control and Payment

- Proximity Technologies
 - Door entry
 - Contactless Smart Cards (MIFARE)
 - Livestock Management

Cost
Security
Networks

Automatic Toll Payment

- EZ-Pass and Title 21 Tolling

Inventory Management

- Retail
 - Wal-Mart / Sam's, Metro, Marks & Spencer
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Cost,
Reliability
Antenna Perf.
IT Infrastructure

Wireless Sensing

- LF Temperature [Opas. et al., 2006]
- HF Biomedical [Fotop. and Flynn, 2006]
- UHF Pressure, Temp. [Sample, 2009]

Packaging
Sensors
Lifetime

Localization

- RTLS for Inventory
- Robotics
 - Localization and Mapping [Burgard '05]
 - Pose Estimation [Deyle et al '08]
 - Object Manipulation [Deyle et al '10]

Antennas,
Waveforms,
Signal-
Processing
Semantic DB

Thank you

- Contact: matt.reynolds@duke.edu
- Collaborators:
 - Jochen Teizer – Georgia Tech
 - Charlie Kemp – Georgia Tech
 - Roian Egnor, Anthony Leonardo - HHMI
- Our Sponsors



National Science
Foundation
CBET-0931924
CMMI-0800858



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