Beyond Identification

Research Opportunities in
Passive Sensing, Computing, and Communication

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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
	  • Wal-Mart / Sam's, Metro, Marks & Spencer
	• Manufacturing and Industrial
	  • Boeing

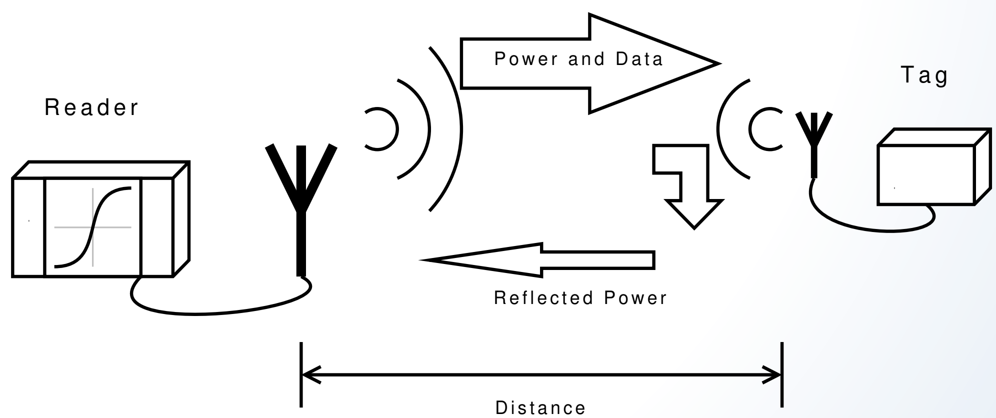
Wireless Sensing	• Time, Temperature [Opas. et al., 2006] • HF Biomedical [Fotop. and Flynn, 2006] • UHF Pressure, Temp. [Sample, 2009]

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?

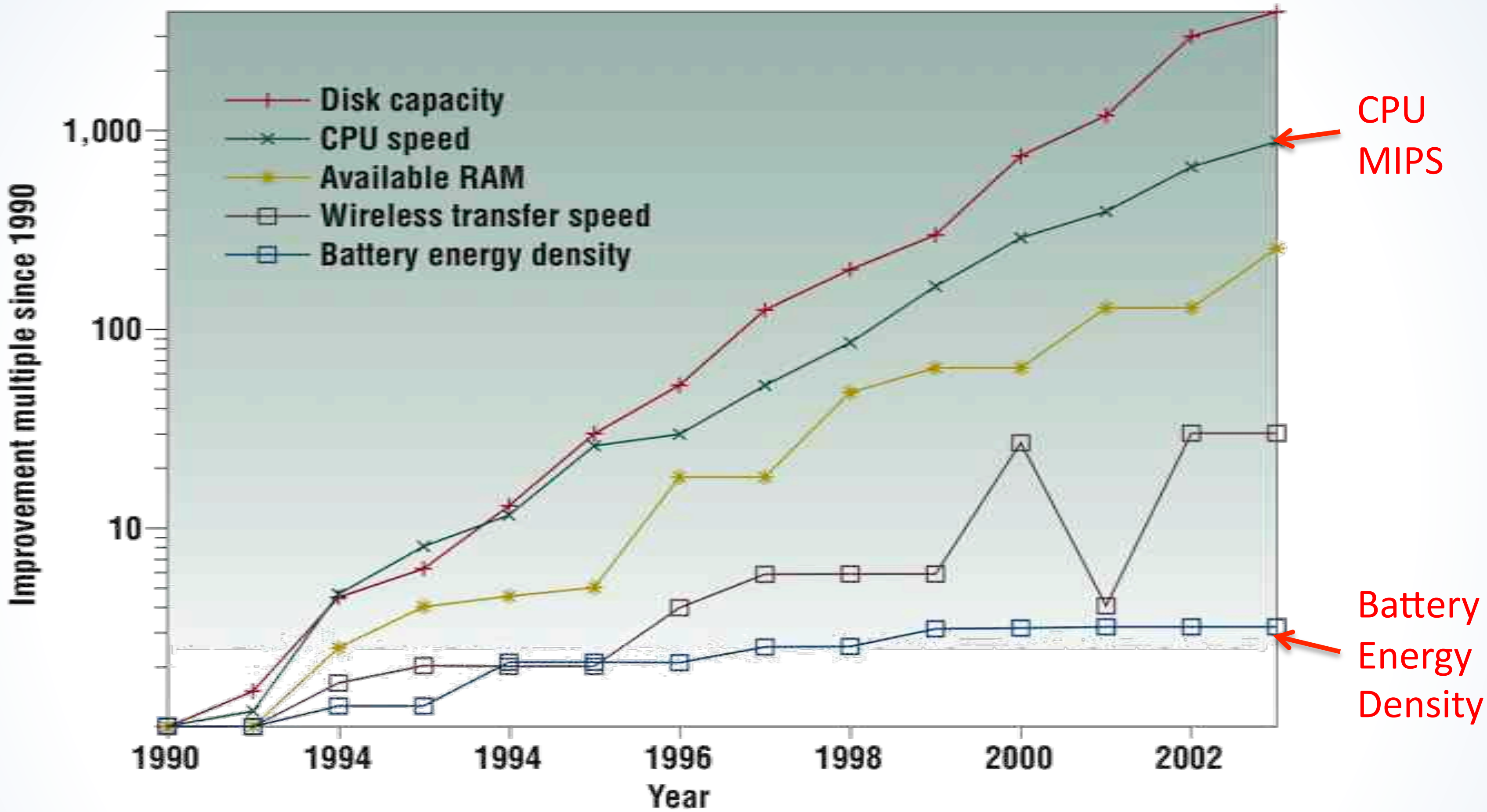
- Passive RFID Technology Spans Electromagnetic Domains
  - LF (Near-Field / Inductive Coupling)
  - HF (Near-Field / Inductive Coupling)
  - UHF and Microwave (Far-Field / Backscatter)

- Focus on Microwatts, MIPS, and MEMS
  - Power Harvesting
  - μW-Computing
  - μW-Communication
  - Integrated Sensing



Passive RFID system

Microwatts and MIPS



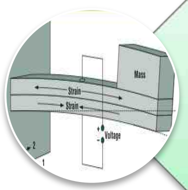
Batteries Don't Follow Moore's Law.

[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

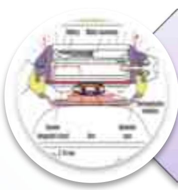


Vibrational Power Harvesting

- 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 (~2μW)

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

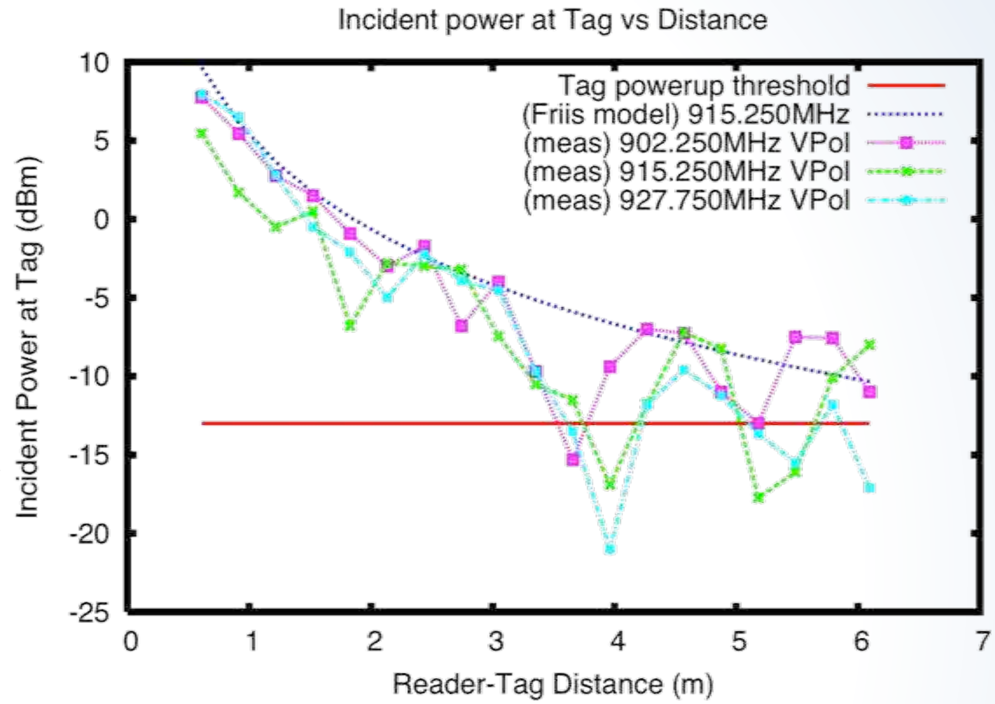
Dragonfly carrying UHF tag

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. Burleson, UMass Amherst]

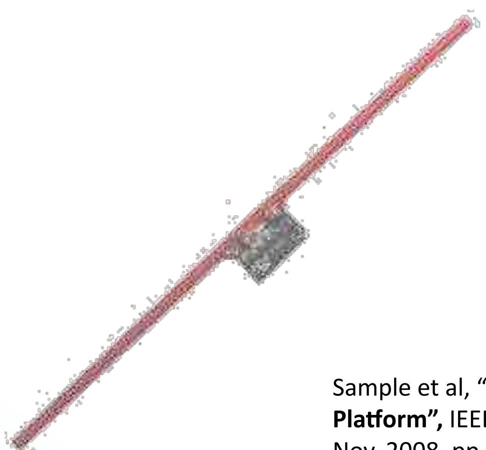


$$P = \frac{G_{TX} G_{RX} \lambda^2}{4\pi d^2}$$

(Only true in an anechoic chamber!)

What's a WiSP?

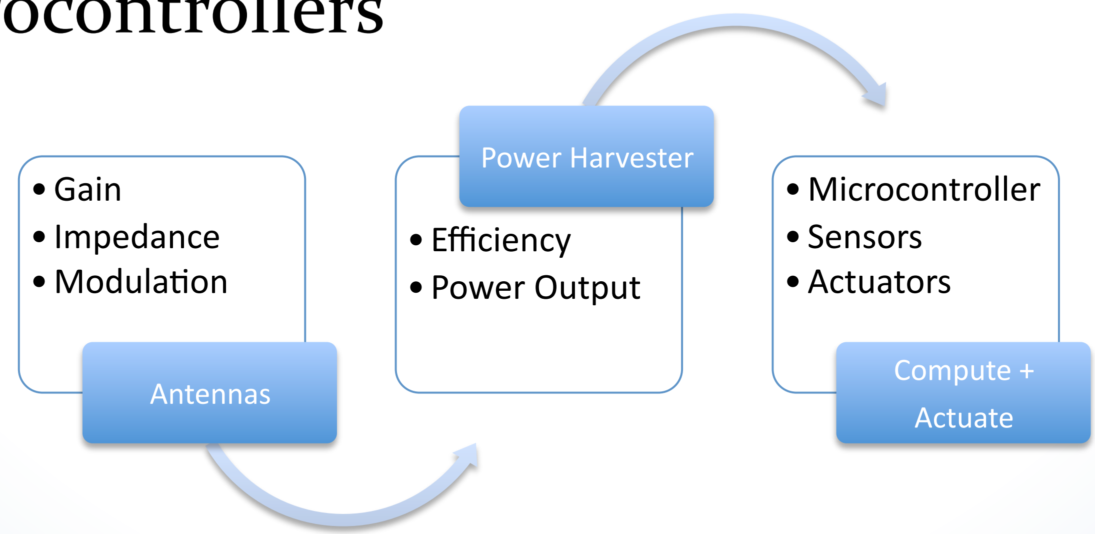
- Wireless Identification and Sensing Platform [Smith, 2005]
  - Concept: Passive RFID with a general purpose computing element
  - Applications: Sensing, crypto, protocol design, etc
  - Inexpensive prototyping of new RFID concepts



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.

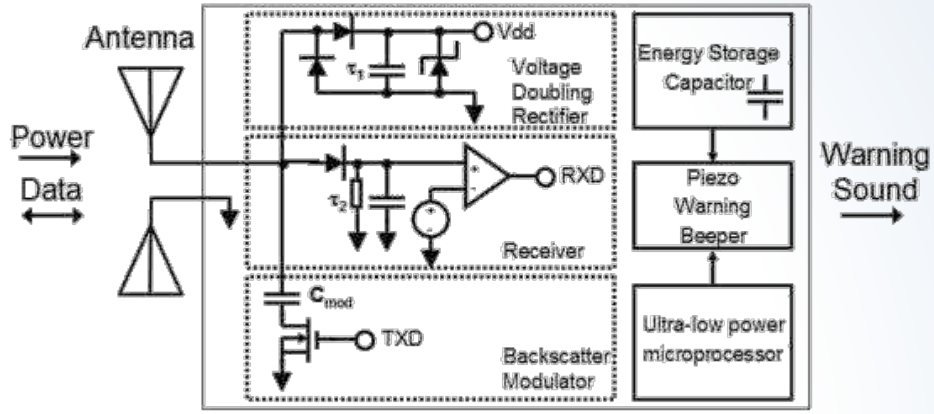
WiSPs at Duke

- 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

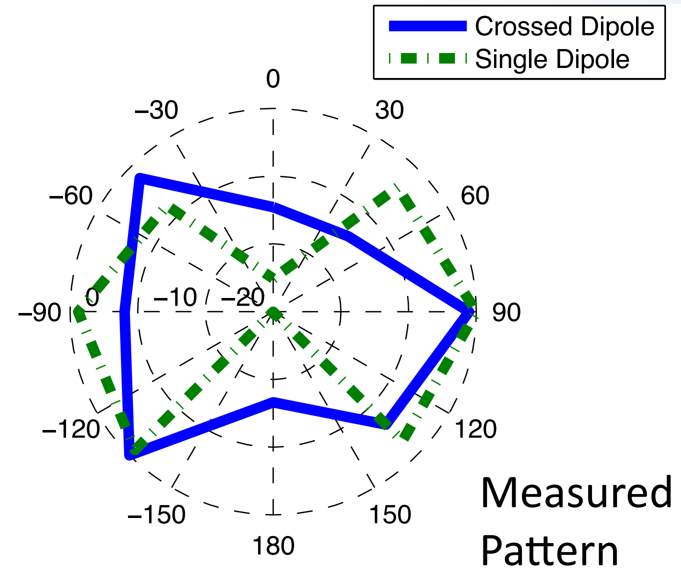
- WiSP + piezo actuator for construction site safety
- Reader mounted to heavy construction equipment
- WiSP in hard hat
- Passive operation allows unlimited lifetime- no batteries to fail



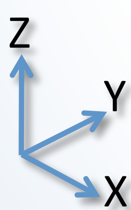
[Thomas, Teizer, Reynolds, 2010]

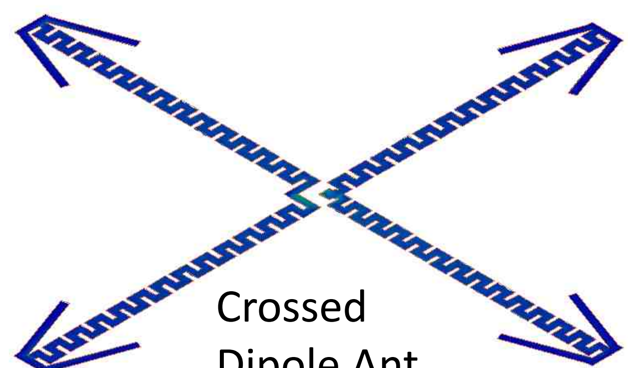
SmartHAT WiSP

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



Measured Pattern



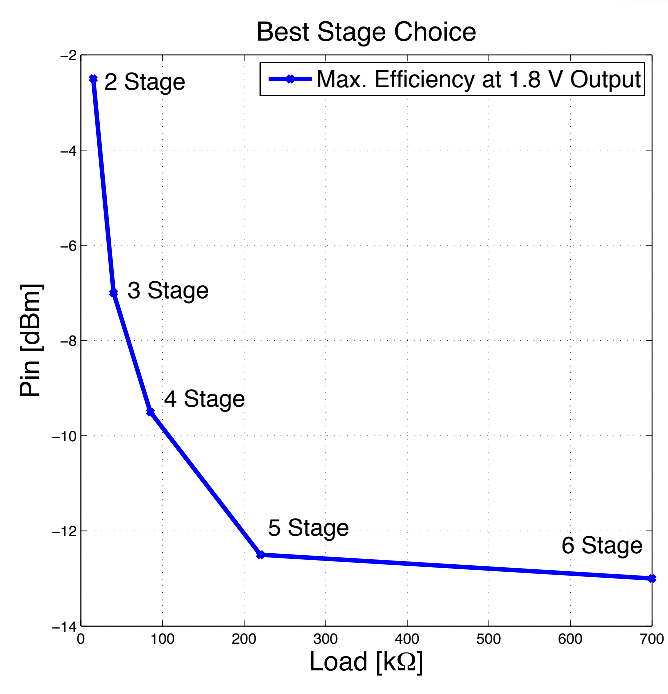


Crossed Dipole Ant.

[Thomas, Teizer, Reynolds, 2010]

Power Harvesters are Nonlinear

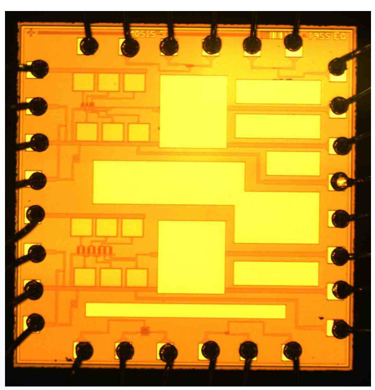
- Selecting operating point is critical in any RFID tag
- This is especially hard to do in a WiSP
  - Charging reservoir capacitor most of the time
  - Sleep current vs MCU current vs actuator current

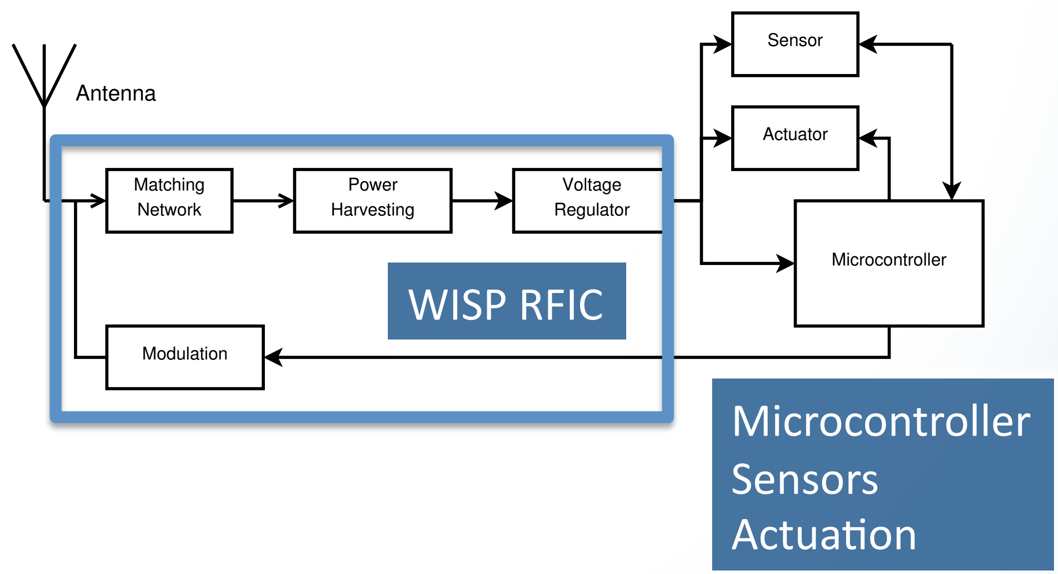


ADS simulations confirmed by measurement at 3,4,5 stages

WiSP Companion RFIC

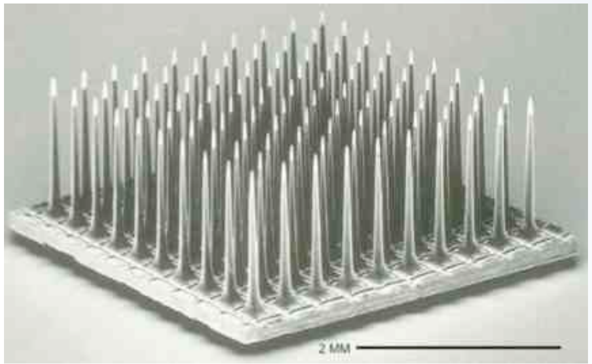
- MOSIS / AMI 0.5u-> 180nm Passive Analog Front End
- Support General Purpose Microcontroller: TI MSP430
  - Flexible protocol + sensor development
  - Extensive development tools
  - Partial Gen2 implementation available from Intel
- RFIC reduces WiSP complexity vs discrete AFE
- Include QAM backscatter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



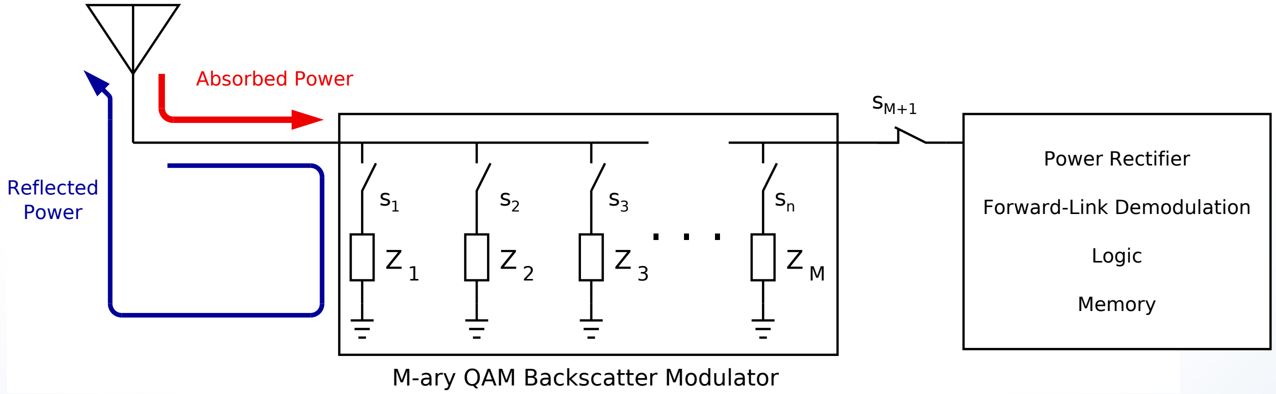


MBPS for μW

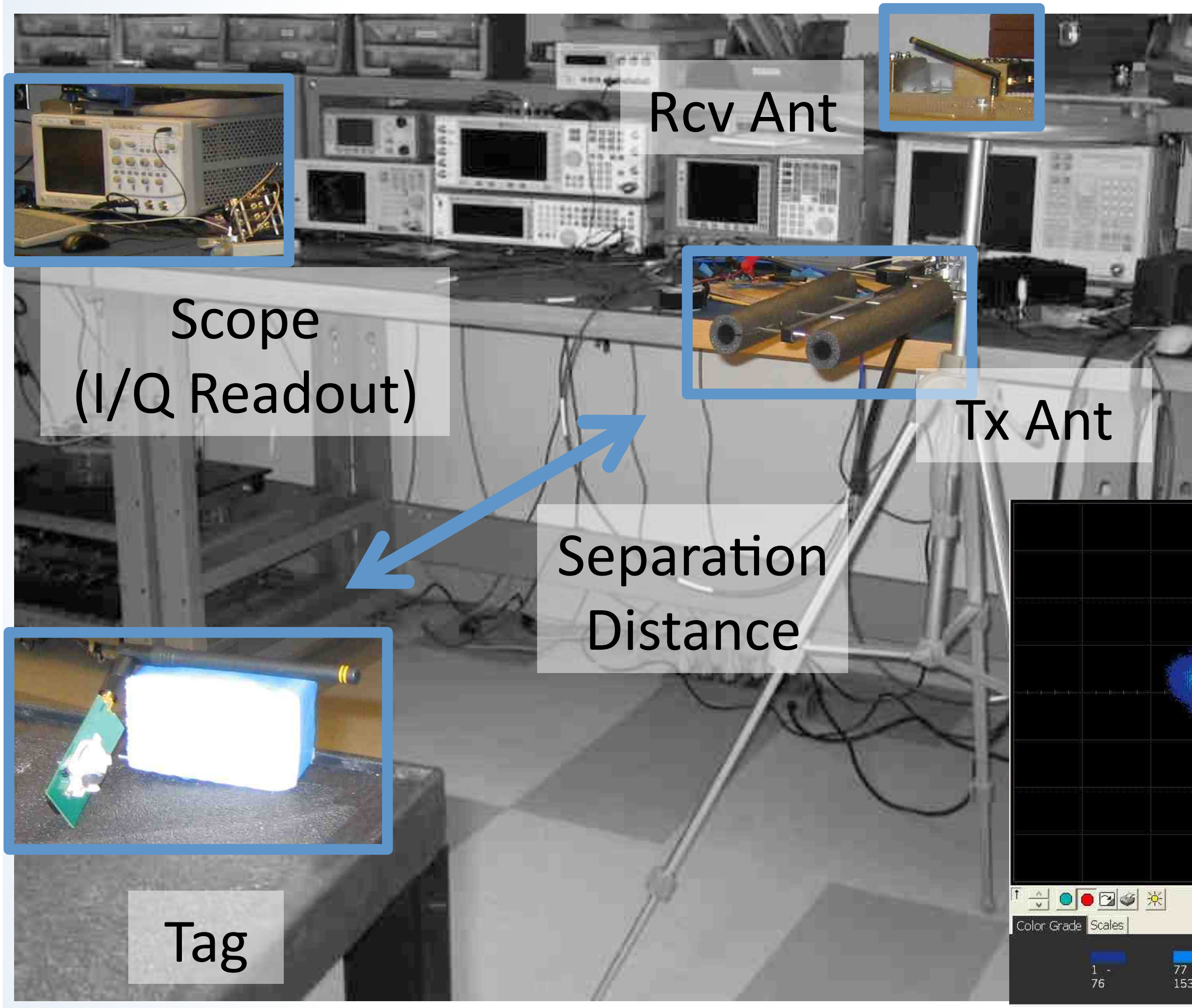
- Today's RFID backscatter links designed for small IDs or user memory blocks
  - Example: ISO18000-6c (Gen2)
  - ASK or PSK (2 states)
  - Up to 640kbps
- Neurotelemetry arrays require a much faster link (>10MBPS)
- Multi-state (QAM) backscatter sends multiple data bits per on-chip clock
- 2x to 4x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

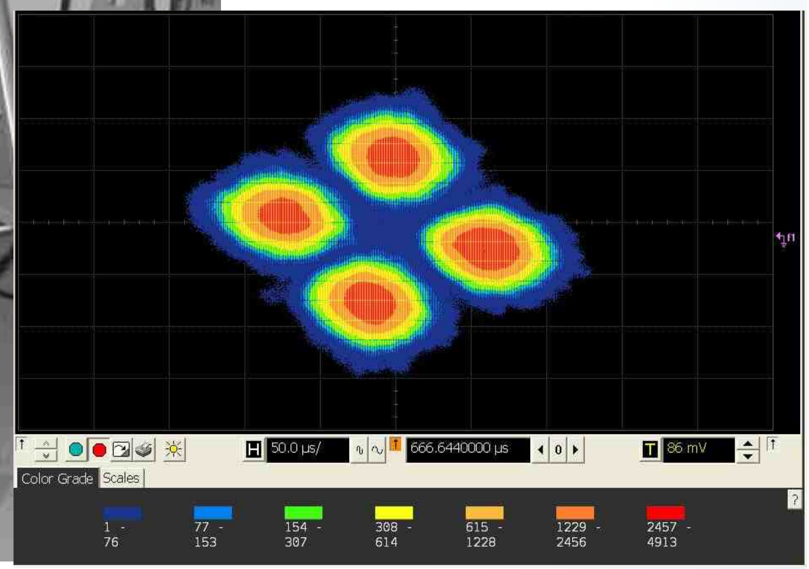


Utah Array Fig: Harrison, R.R., "The Design of Integrated Circuits to Observe Brain Activity," *Proceedings of the IEEE, vol.96, no.7, pp.1203-1216, July 2008*



QAM Backscatter Over the Air

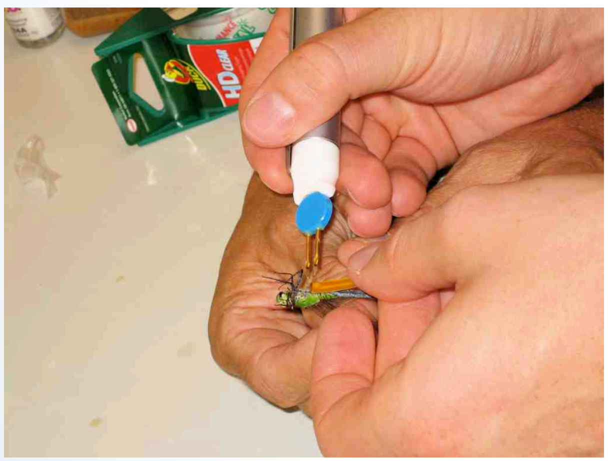


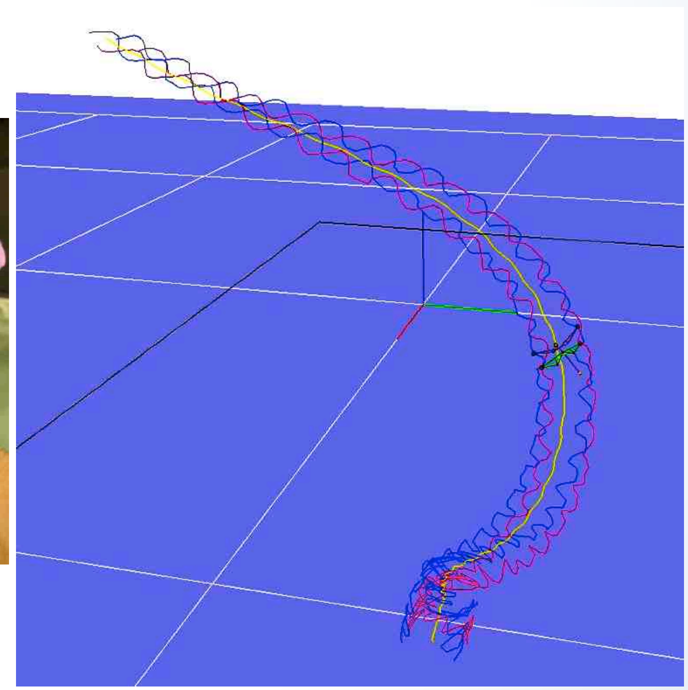


[Thomas, IEEE RFID 2010, Session 4B]

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





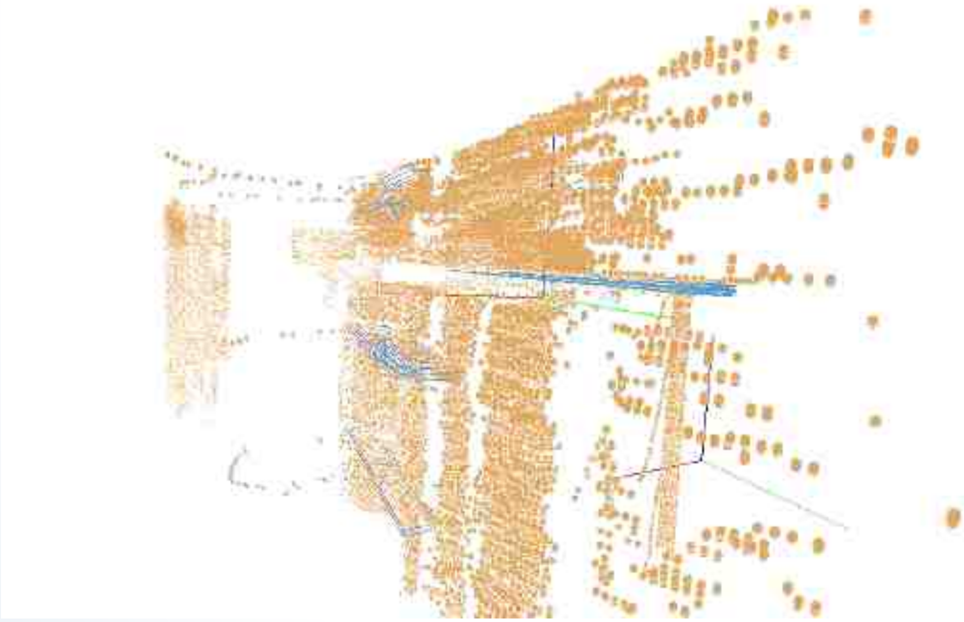
[Leonardo Lab, HHMI]

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:

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

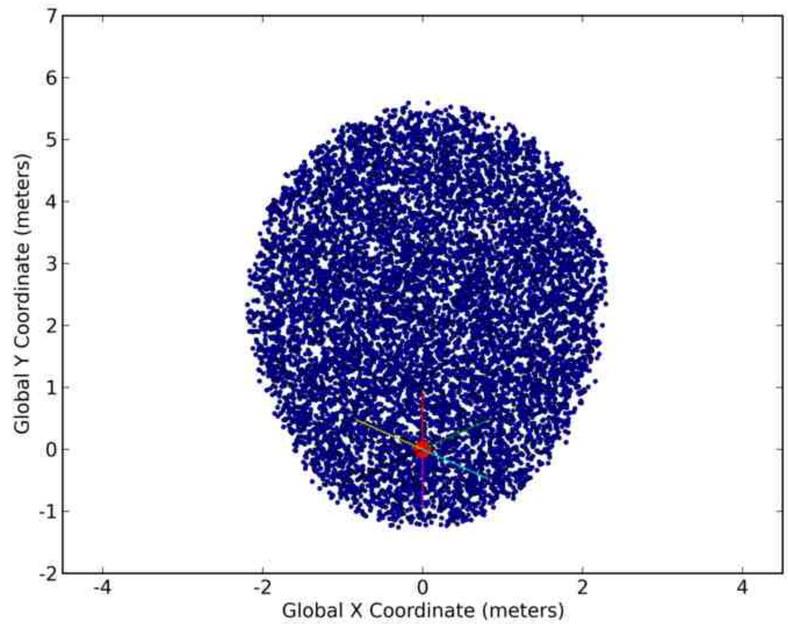
Sensor Model (RFID signal propagation model)

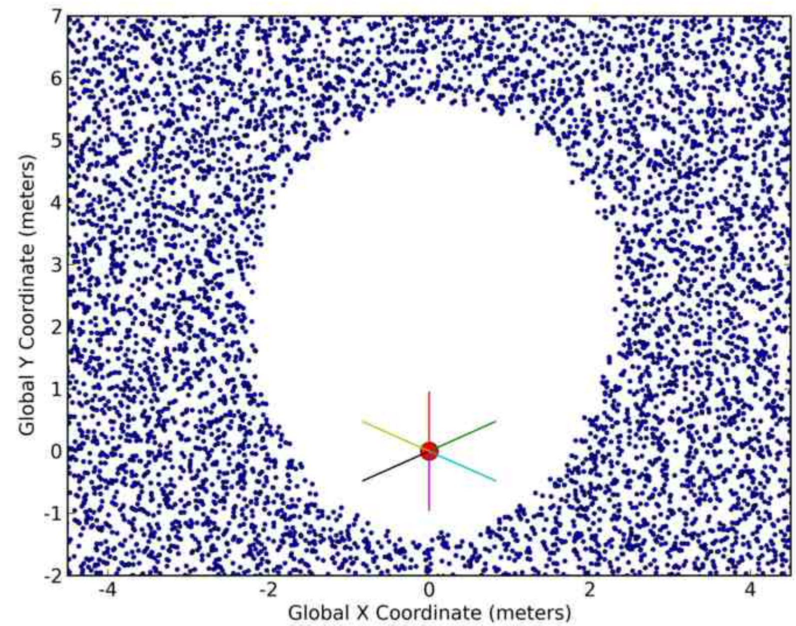
Robot Motion Model (Odometry)

RFID Sensor Model

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

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

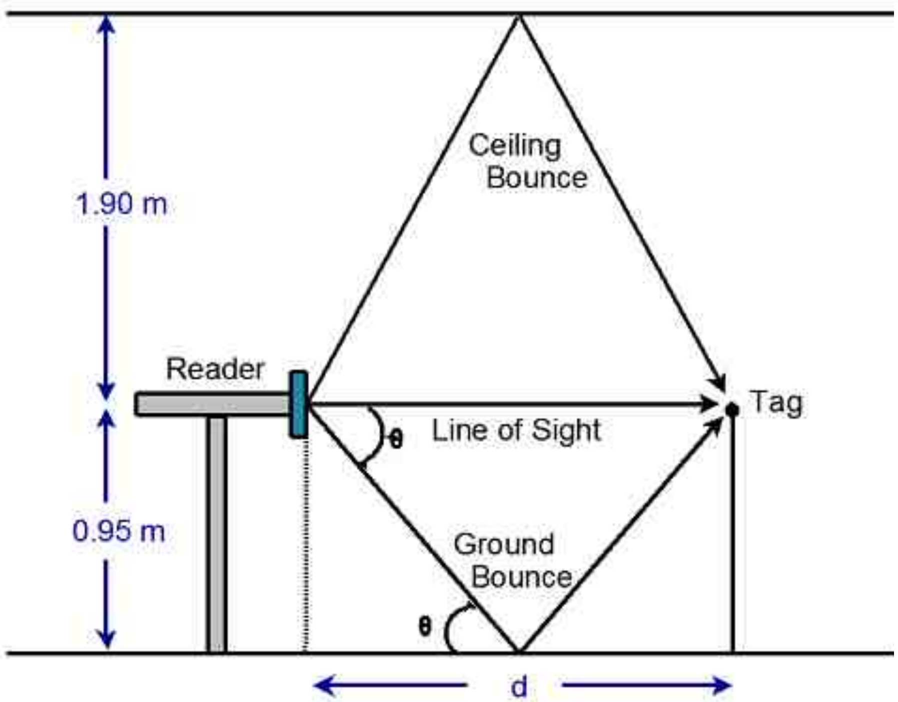


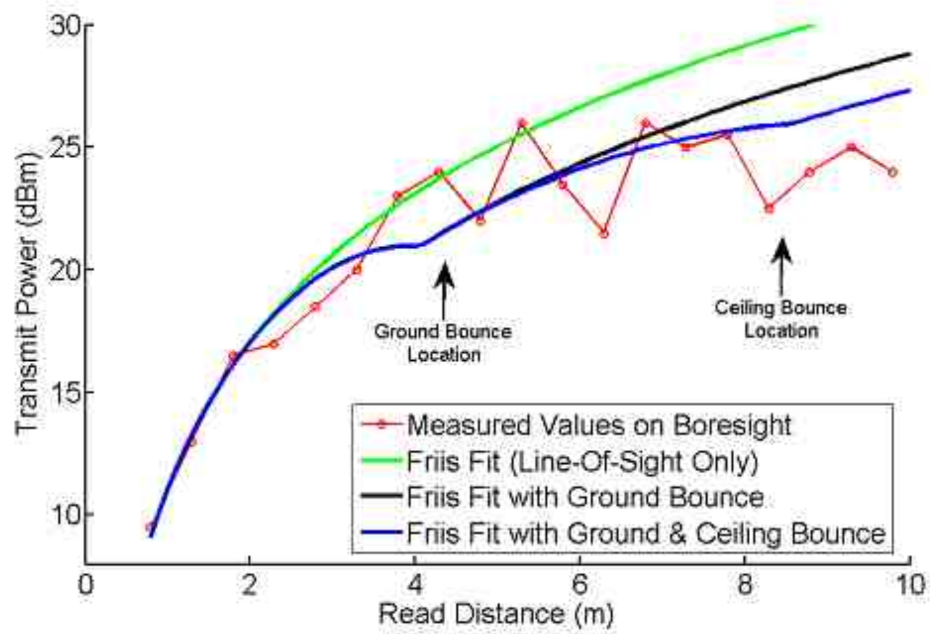


Express probability of tag read using tag powerup threshold- Need antenna radiation pattern and propagation model with multipath.

Multipath Model

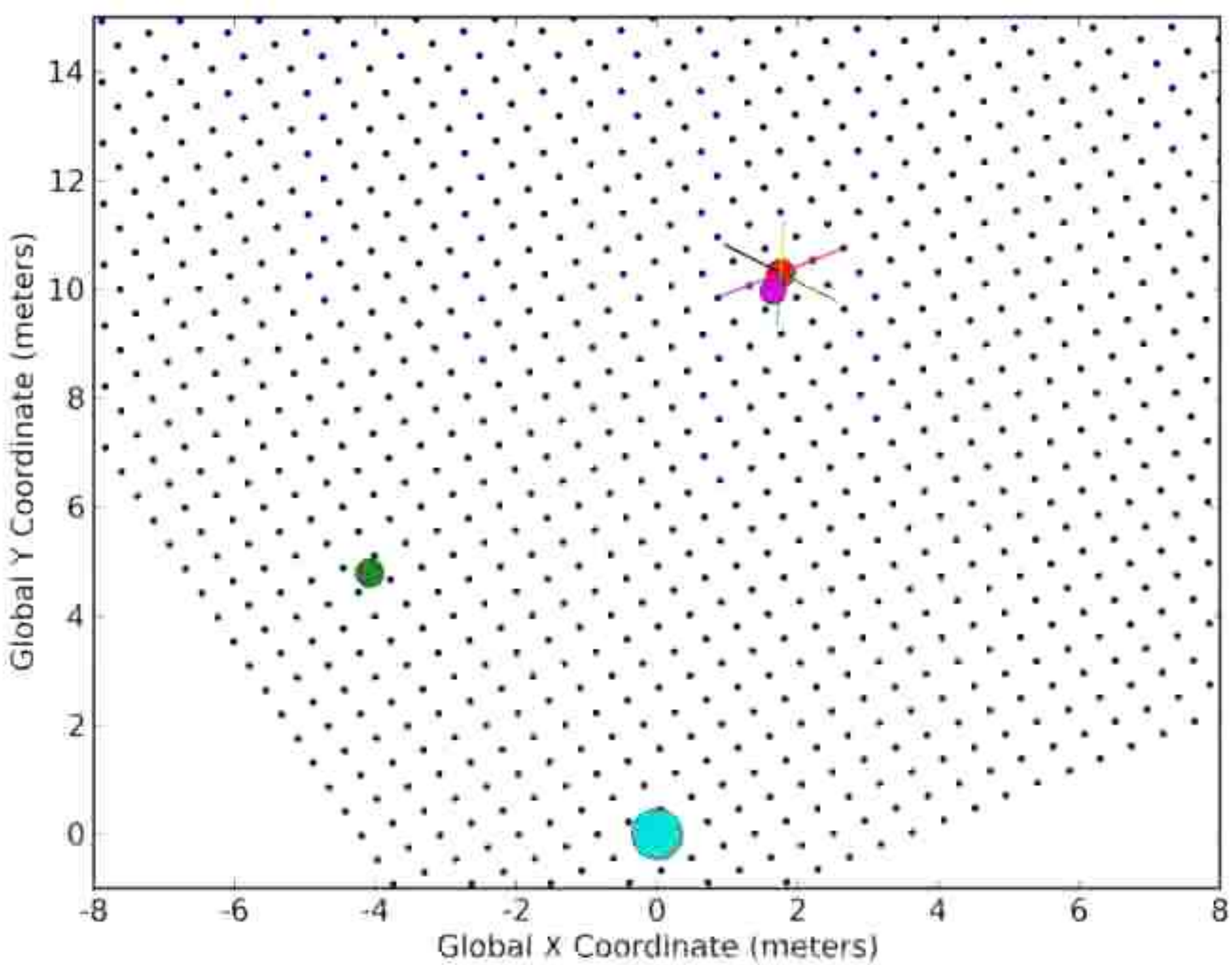
$$P_{tag}^{inc} = P_{rdr} \cdot CL \cdot G_{tag} \cdot \left[\sum_{\text{all paths}} G_{rdr}(\theta) \cdot PL \right]$$





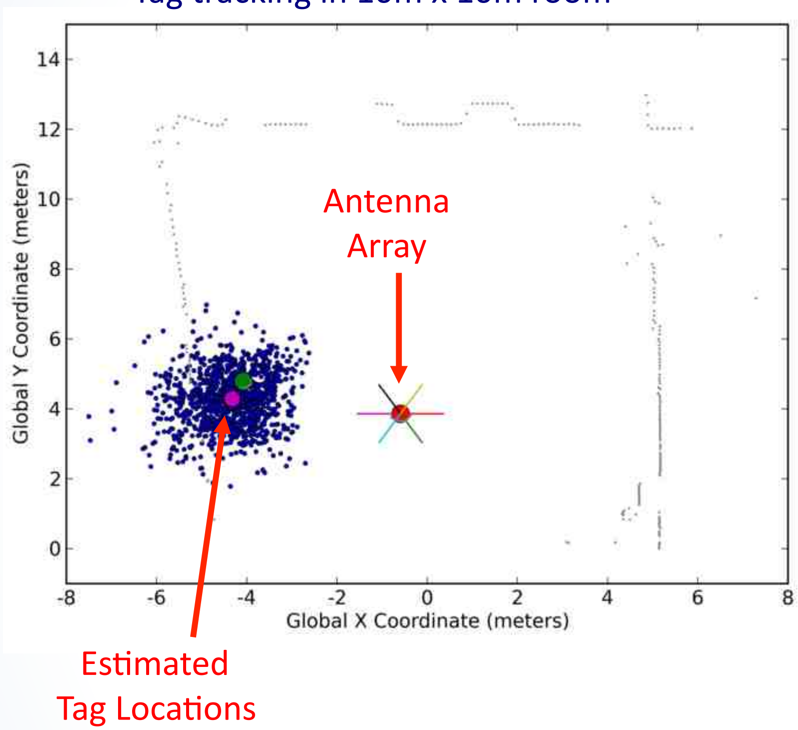
Ground bounce and ceiling bounce are dominant and allow model simplification for computational tractability.

Particle Filter during Robot Motion



Particle Filter Results

Tag tracking in 10m x 10m room



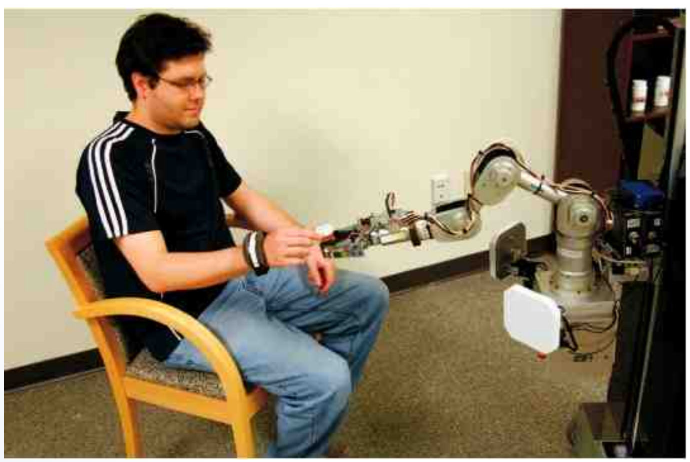
Range	Error Measures	Line-Of-Sight Only	With Ground & Ceiling Bounce
All d_{actual}	d_{error}	μ=0.71m σ=0.45m	μ=0.69m σ=0.42m
	$d_{relative}$	μ=16.2% σ=6.8%	μ=15.9% σ=6.6%
	θ_{error}	μ=6.11° σ=4.19°	μ=6.11° σ=4.19°
$d_{actual} \leq 4$ m	d_{error}	μ=0.40m σ=0.20m	μ=0.41m σ=0.21m
	$d_{relative}$	μ=13.3%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

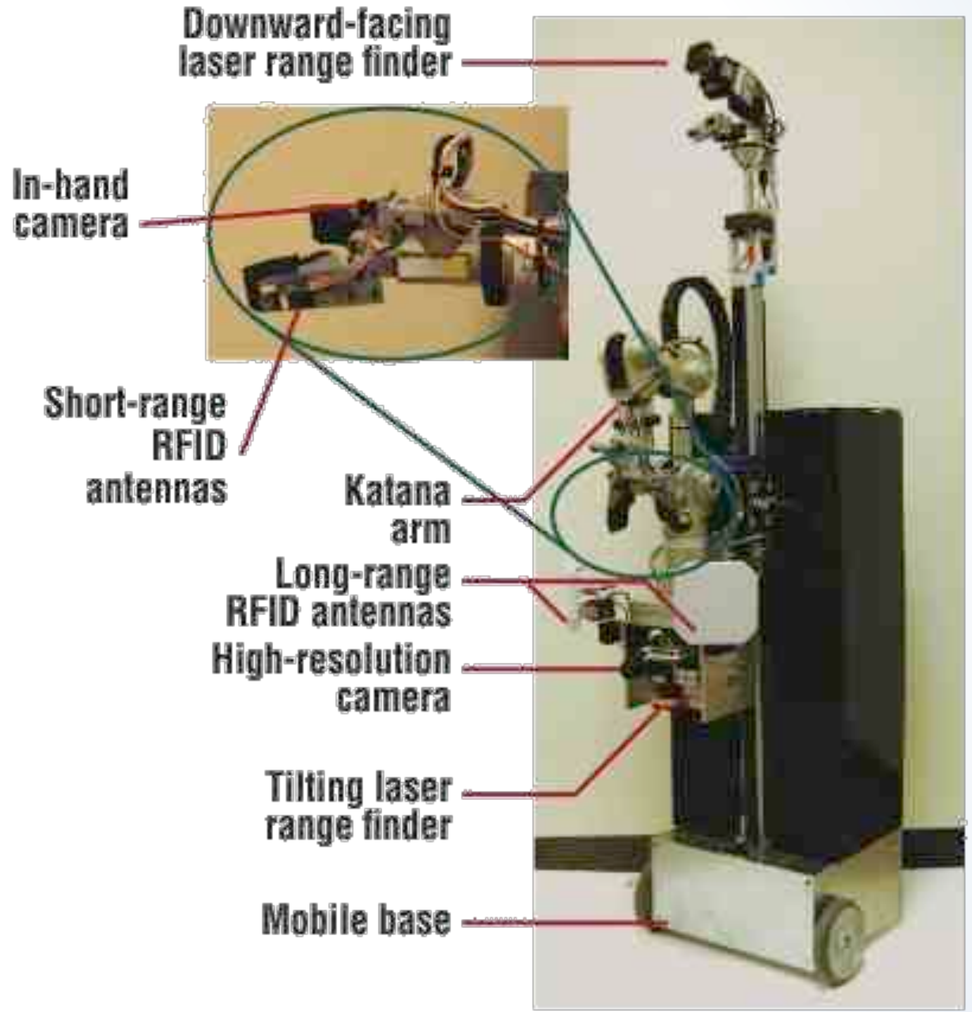
TABLE I
PARTICLE FILTER ACCURACY AFTER CONVERGENCE

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

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





RFID Guided Robots for Pervasive Automation, IEEE Pervasive Computing, April 2010

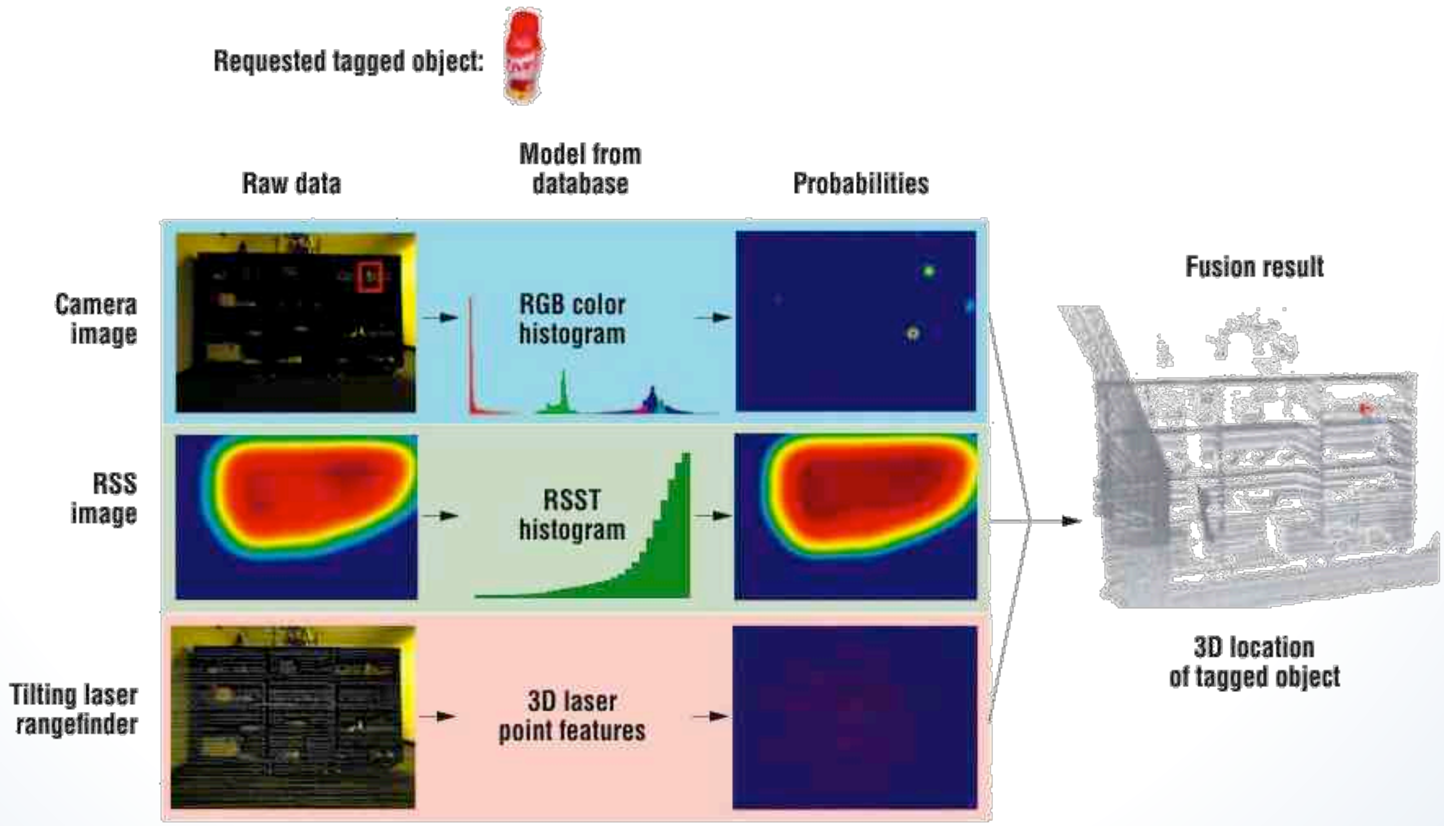
PPS Tags: Physical, Perceptual, Semantic

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

```
'properties':    {'type': 'ada light switch',
                 'name': 'A D A light switch 1',
                 'pps_tag': 'dycem',
                 'change': 'overall brightness',
                 'switch_travel': 0.02,
                 'height': 1.22,
                 'on_plane': True,
                 'direction': 'up',
                 'ele': {'color_segmentation':
                        [[34, 255], [157, 255],
                        [0, 11]]},
                 },

'actions':       {'off': 'push_bottom',
                 'on': 'push_top'},

'push_bottom':   {'force_threshold': 3.0,
                 'height_offset': -0.02
                 '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

Where are the Research Challenges?

Application	Examples	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
	• Manufacturing and Industrial
	  • Boeing
		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

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  - Charlie Kemp – Georgia Tech
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