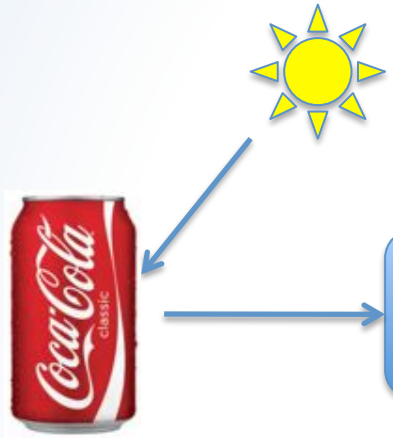
What Is That?

RFID in Machine Perception

Matt Reynolds
Department of Electrical and Computer Engineering
Duke University

What Is That?

Approach I : Computer Vision



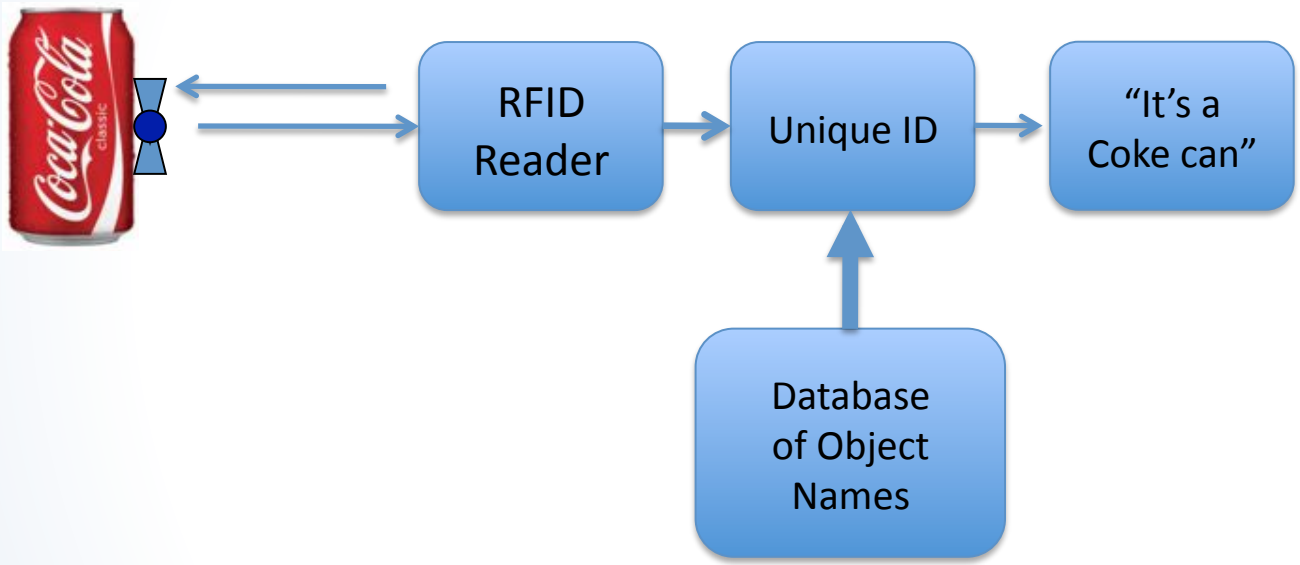
Camera → Lighting Compen-sation → Color / Edge Detection → Object Separation → Model Fitting → Rank by Probability → "It's probably a Coke can"

Giant Database of Object 3D Models → Model Fitting

P(Detection) << 1
P(False Alarm) high
Lots of computation

What Is That?

Approach II : RFID



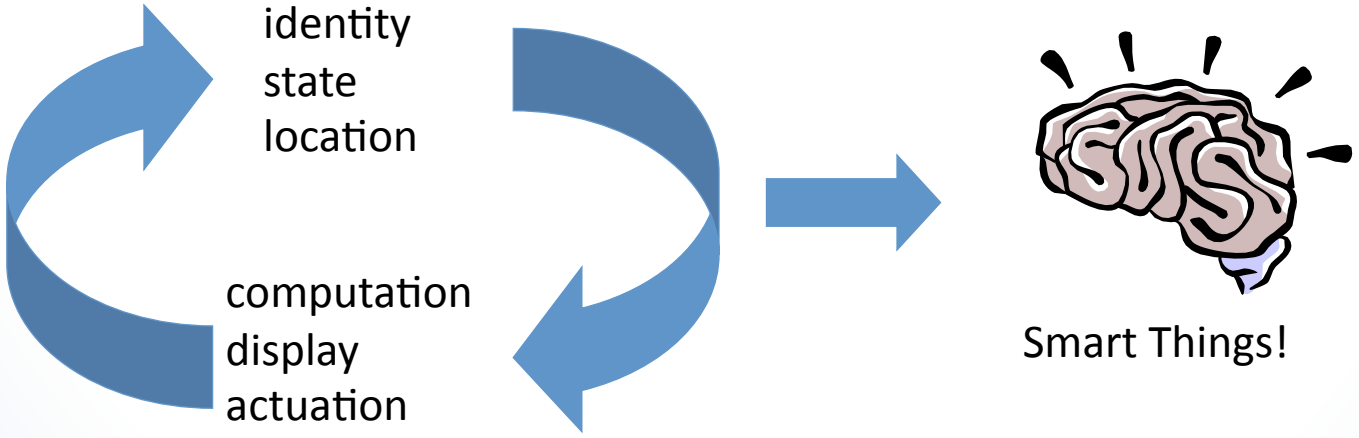
P(Detection) high
P(False Alarm) zero

The Internet of Things

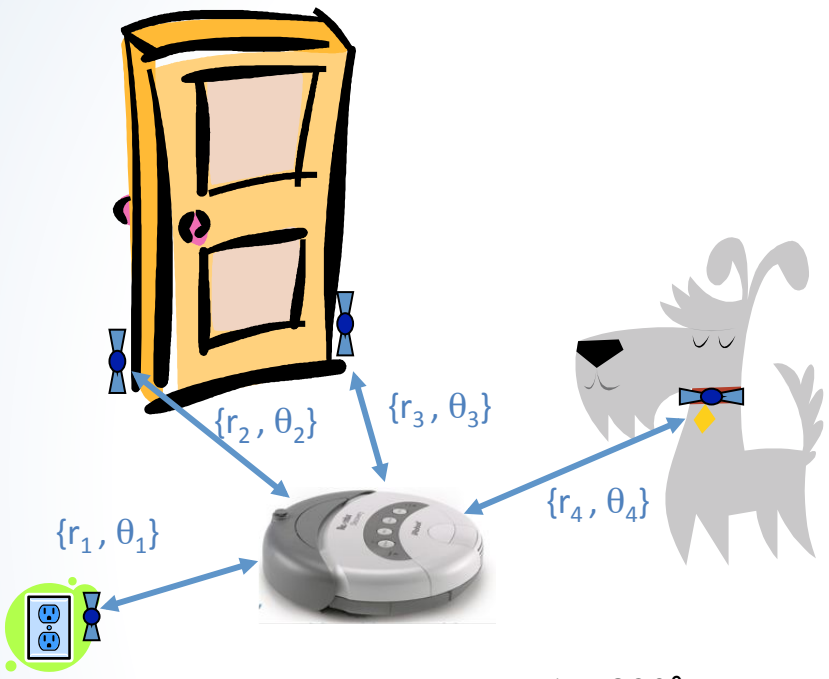
- **Tags are 'handles' for physical things in the virtual world.**

- Today, tags provide *identity*
- Everything will have tags
  - Everyday objects, people, robots, pets, physical spaces…
  - In the future, tags will provide *identity*, *state*, and *location*
  - Tags will talk to each other

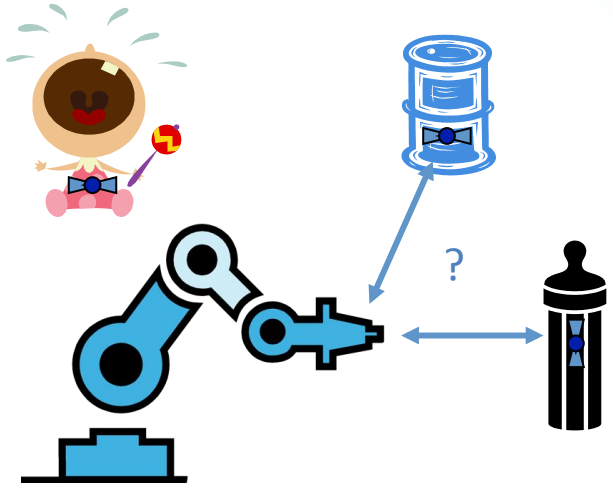
- Close the loop: add *computation, display, and actuation*



Where to put *world state*?



- ***Object*** **{4}** ***At*** **{1m,320⁰}** ***Is*** **{Dog}**
- ***Properties*** **{Dog} {**
  - **Autonomous && Is_Alive && Is_Valuable && Creates_Dirt && Roomba_Quiet && Avoid{2m} && If_Chased{Hide} }**



Object {1} *At* {0.1m,45⁰} *Is* {Oil_Can}

Object {2} *At* {0.1m,90⁰} *Is* {Bottle}

Object {3} *At* {1.0m,270⁰} *Is* {Human}

Properties {Oil_Can} {
  Mobile_Object && Contains{Robot_Oil} && Keep_Upright && Is_Flammable }

Properties {Bottle} {
  Mobile_Object && Not_Alive && Currently_Contains{Milk} && Keep_Upright && Temp_Max{10C} }

Properties {Human} {
  !Eat{Robot_Oil}...

Stigmergy as a paradigm for behavior

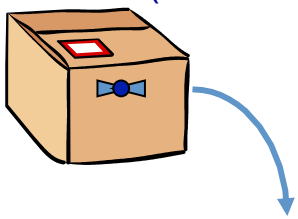
Every tagged object becomes a packet.

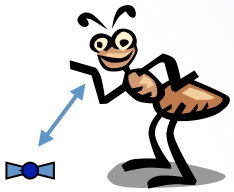
Objects can be routed by the network

(packet switching)

Or objects can follow state left in the environment by other objects

(swarming)





- Grassé, P.-P. **La reconstruction du nid et les coordinations interindividuelles- La théorie de la stigmergie**, *Insectes Sociaux* 6: 41-84 (1959)
- Brooks, R. A. **Intelligence without Reason**, *Proceedings of 12th Int. Joint Conf. on Artificial Intelligence*, Sydney, Australia, August 1991, pp. 569-595.

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

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

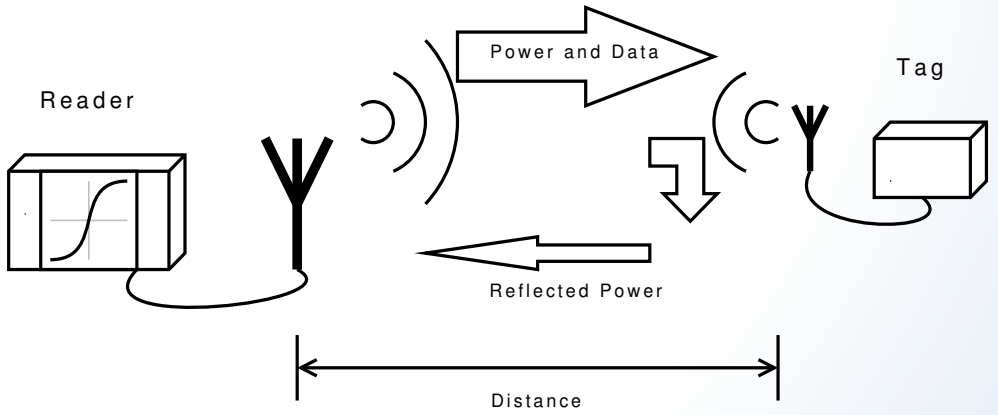
Wireless Sensing	• Time, Temperature [Opas. et al., 2006] • HF Biomedical [Fotopolous and Flynn, 2006] • UHF Pressure, Temp. [Sample, 2009]

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

What can we learn from passive RFID?

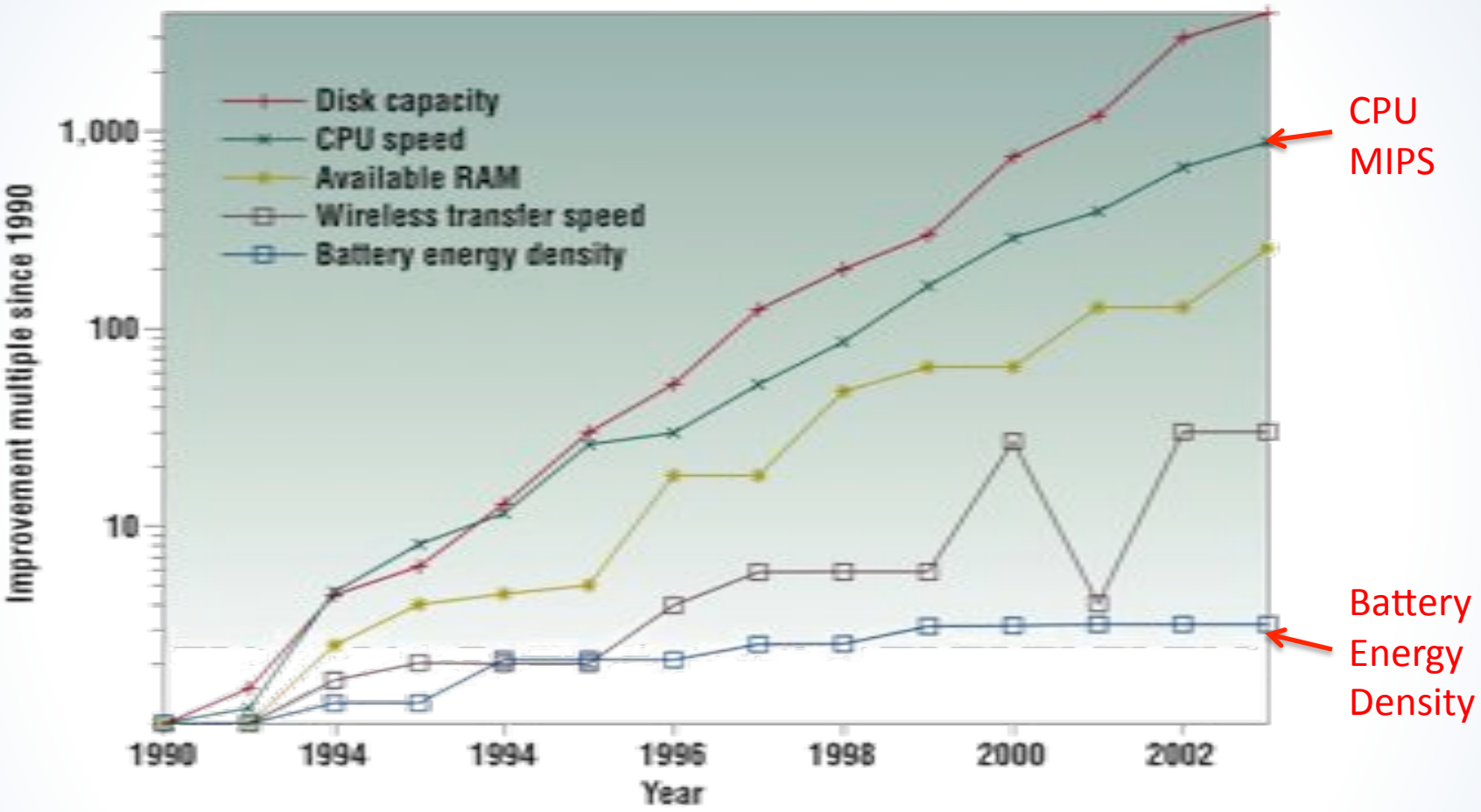
- Passive RFID Technology Spans Electromagnetic Domains
  - LF (Near-Field / Inductive Coupling)
  - HF (Near-Field / Inductive Coupling)
  - UHF and Microwave (Far-Field / Backscatter)

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



Passive RFID system

Microwatts and MIPS



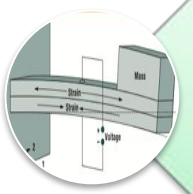
Batteries Don't Follow Moore's Law.

[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

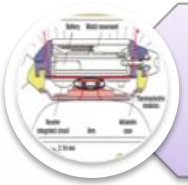


Vibrational Power Harvesting

- 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)

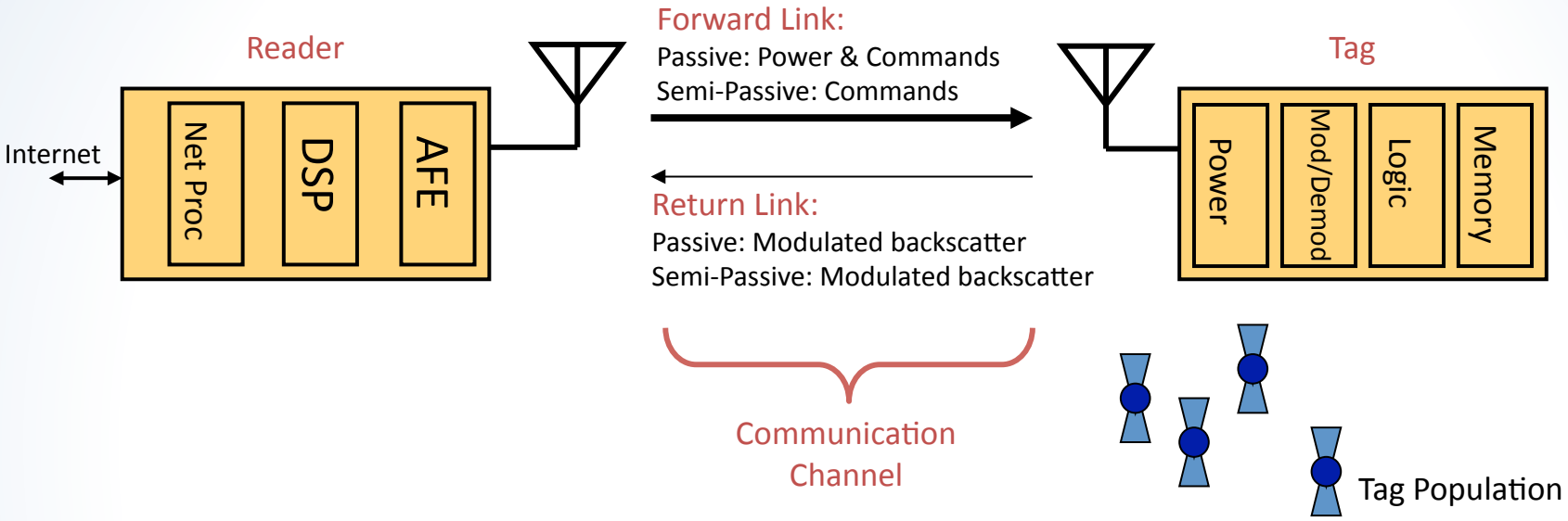
Microwatts, MIPS, and MEMS

- 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

RFID System Model

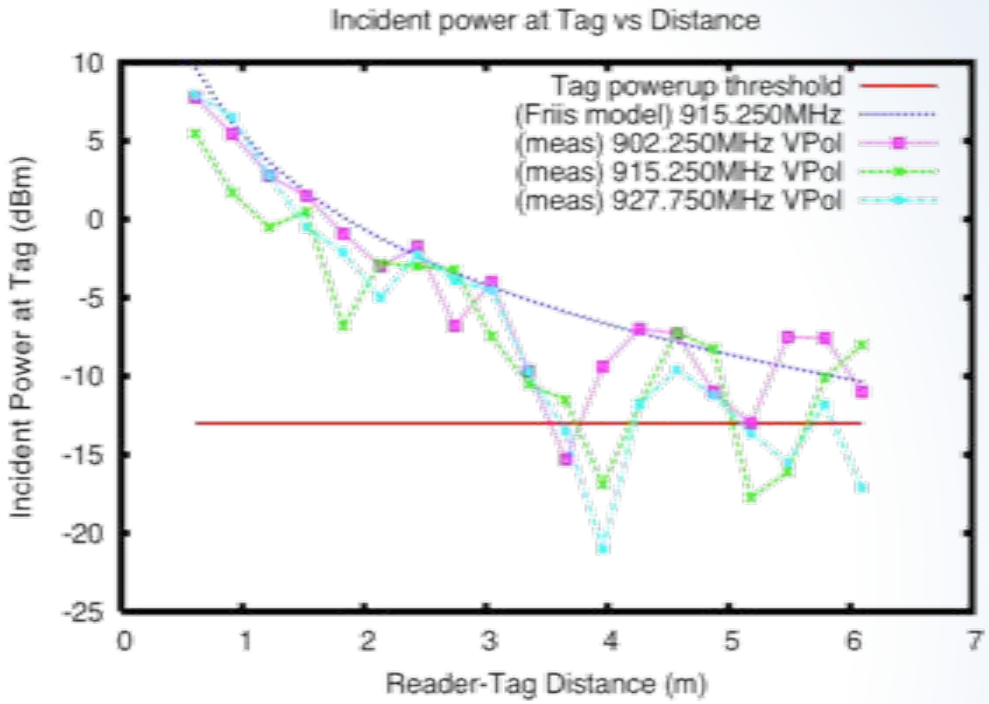


Engineering Challenges:

- Indoor channel (multipath)
- Spectral reuse (dense reader / dense tag environments)
- Full-duplex operation – simultaneous TX and RX
- Jammer immunity (self-jammer as well as external jammer)

Forward Link: Power + Data from AP

- Power Budget
  - 100 μW @ 6 m
  - 10 μW @ 20 m
- Real environments have lots of multipath
- Polarization diversity helps



$$P = \frac{G_{TX} G_{RX} \lambda^2}{4\pi d^2}$$ (Free space model)

- Need techniques for computing with unreliable power

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

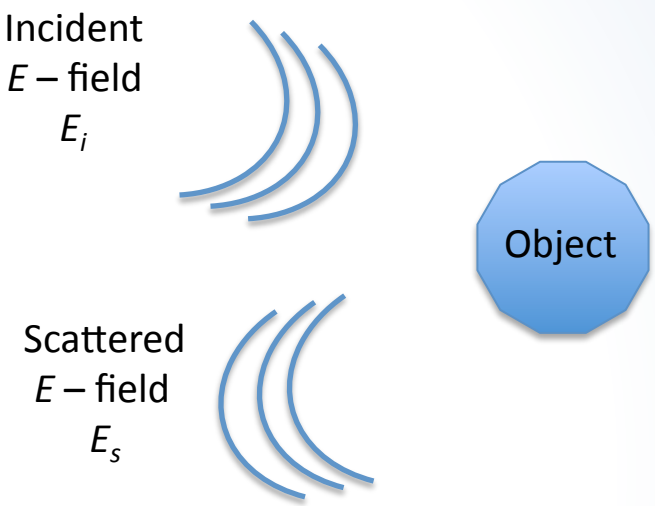
Return Link: Understanding backscatter

- Reflective objects have a *radar cross section* σ

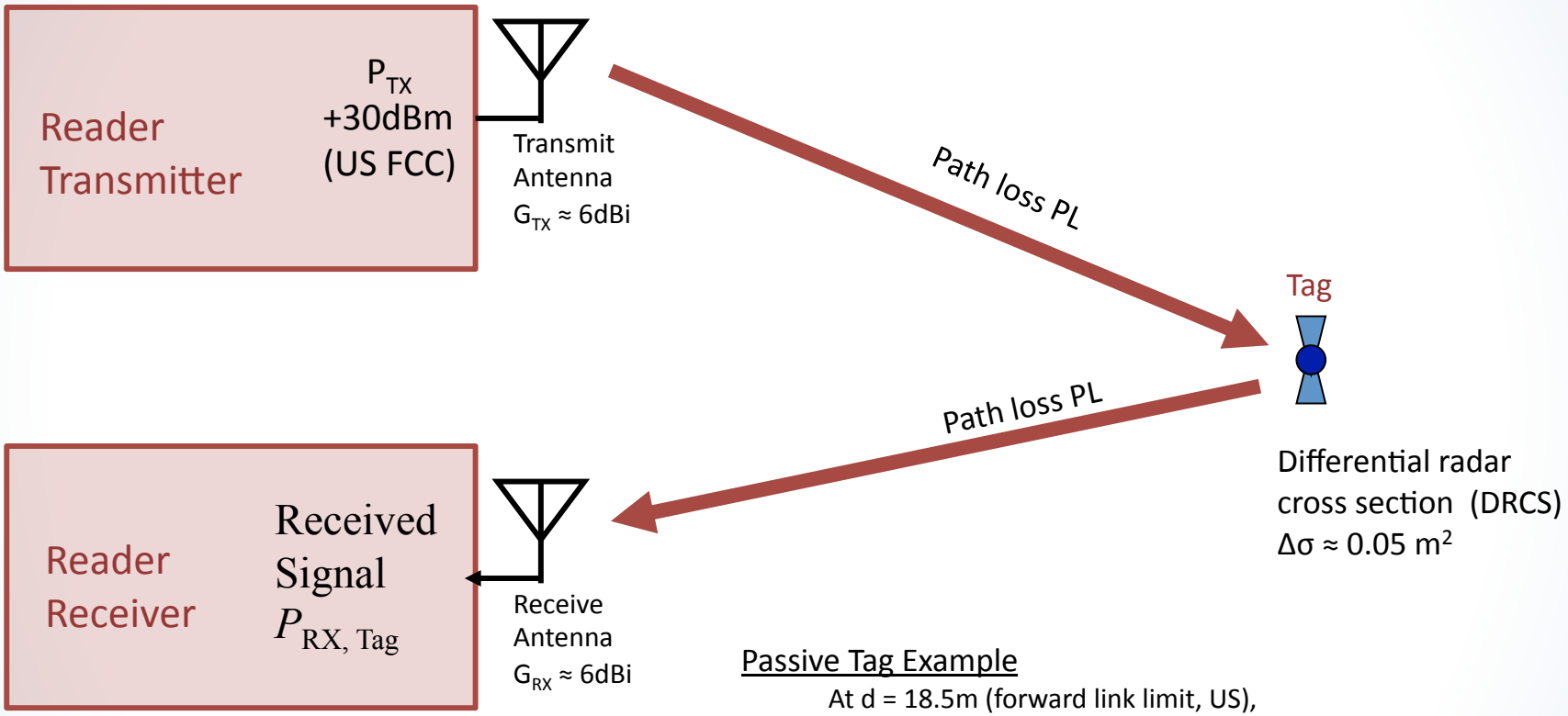
$$\sigma = \lim_{d \to \infty} \left[4\pi d^2 \frac{|E_s|^2}{|E_i|^2} \right]$$

- Dimensions of RCS are area (m^2) but RCS is not a physical area!
- The radar equation can be used to estimate backscattered signal power:

$$P_r = \frac{P_T G_T G_R \lambda^2 \sigma}{(4\pi)^3 d^4} \quad \Rightarrow \quad \frac{1}{d^4}$$



First-Pass Backscatter Model



$$P_{RX,Tag} = \frac{P_{Tx} G_{Tx} G_{RX} \lambda^2 \Delta\sigma}{(4\pi)^3 d^4}$$

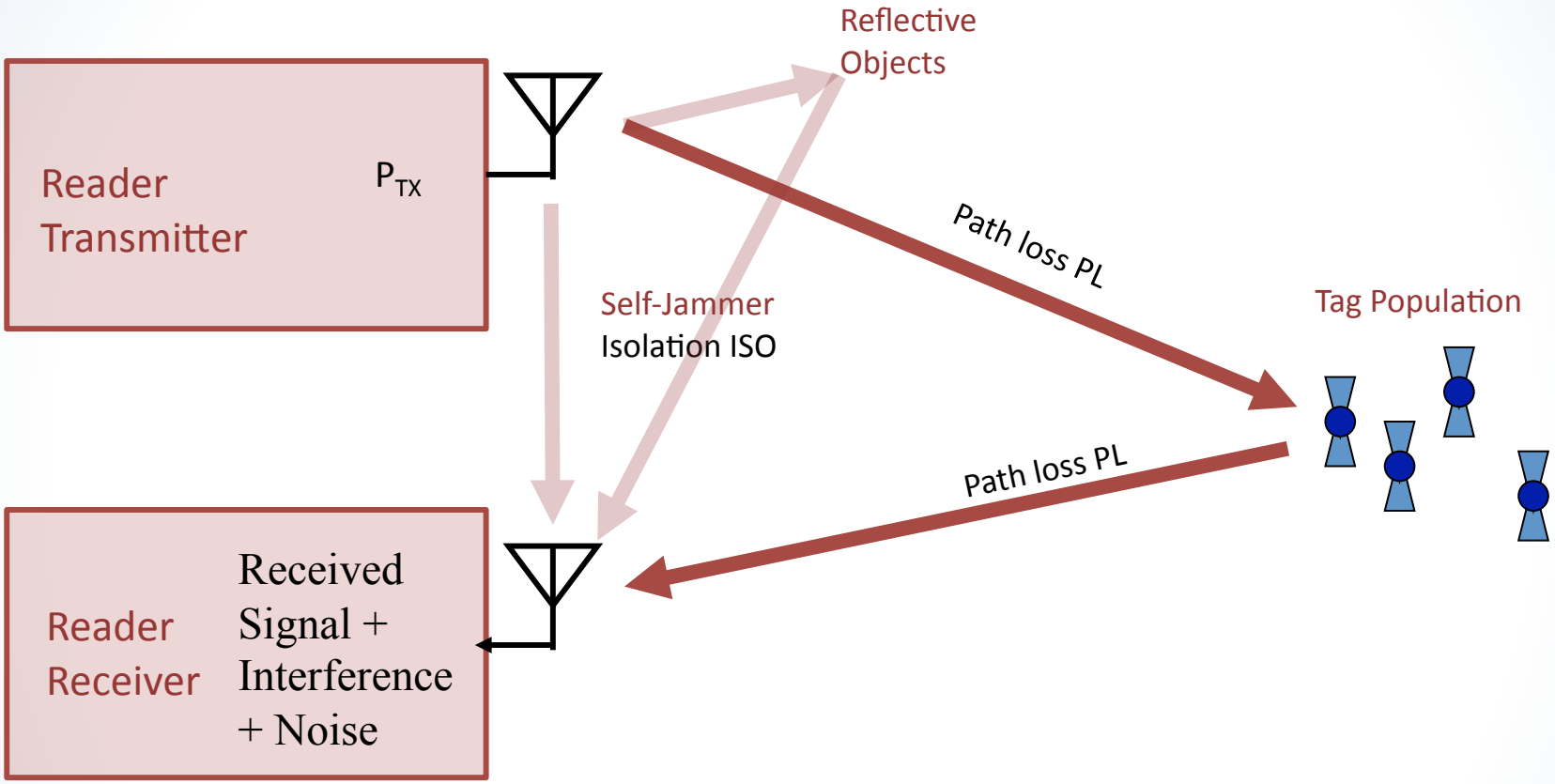
Passive Tag Example

At d = 18.5m (forward link limit, US),
$\Delta\sigma \approx 0.05$ m²
$P_{RX,Tag} \approx$ -94 dBm

Semi-Passive Tag Example

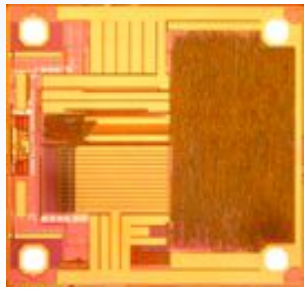
d = 100 m (claimed range of some SP tags, US)
$\Delta\sigma \approx 0.05$ m²
$P_{RX,Tag} \approx$ -123 dBm

Signals actually observed by reader

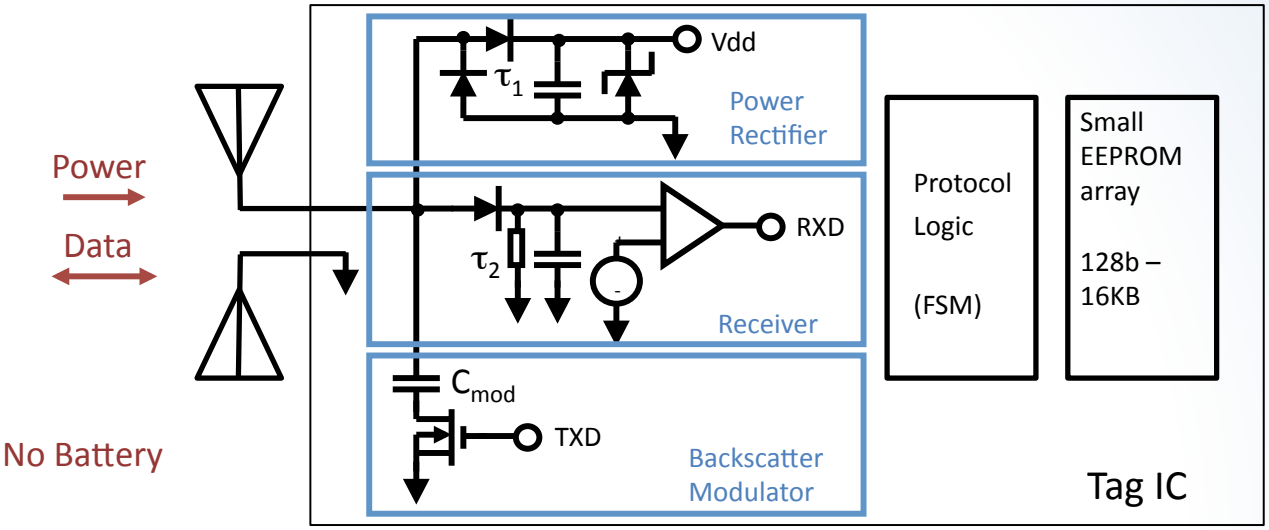


$$P_{\mathrm{RX,Total}} = \underbrace{P_{\mathrm{RX,Tag}}}_{\text{Signal of Interest}} + \underbrace{(P_{TX-ISO}) + \sum P_{TX-REFL} + n}_{\text{Interference+Noise}}$$

Passive UHF RFID tag



~ 750 μm



Passive tags derive power from incident RF to operate internal logic

- -20dBm (10μW) is current state of the art for Gen 2 passive tags
- Close to practical limits for CMOS logic

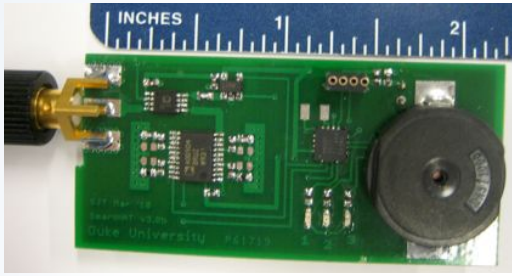
Tags receive ASK from reader

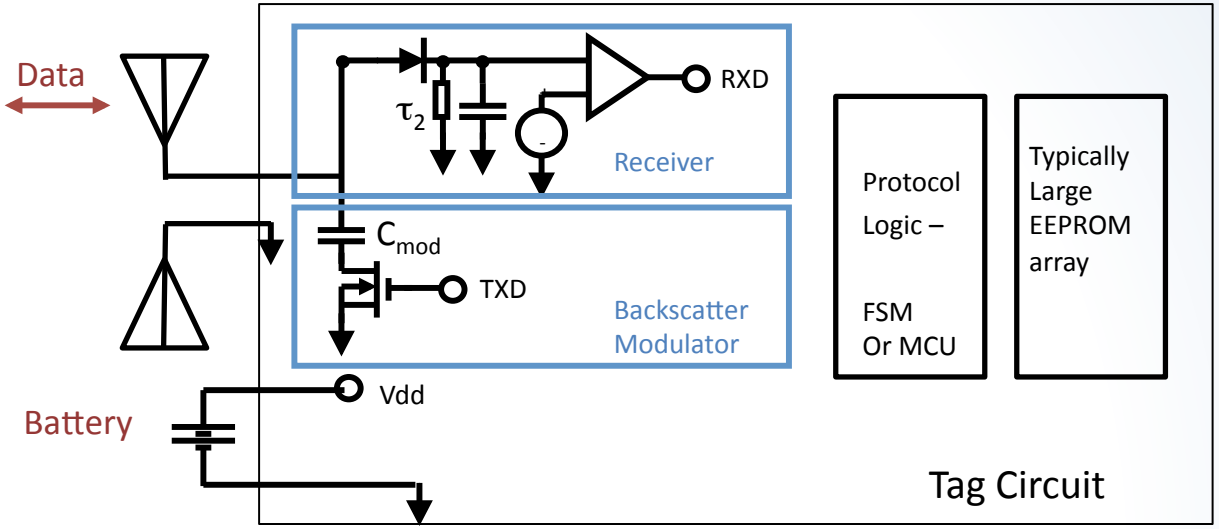
- Simple, low power envelope detector

Tags transmit ASK or PSK via modulated backscatter

- Backscatter moves complexity from tag to reader

Semi-Passive UHF RFID tag





Semi-passive tags use battery power to run their logic

- Potentially much longer read range

Tags receive ASK from reader

- Simple, low power envelope detector

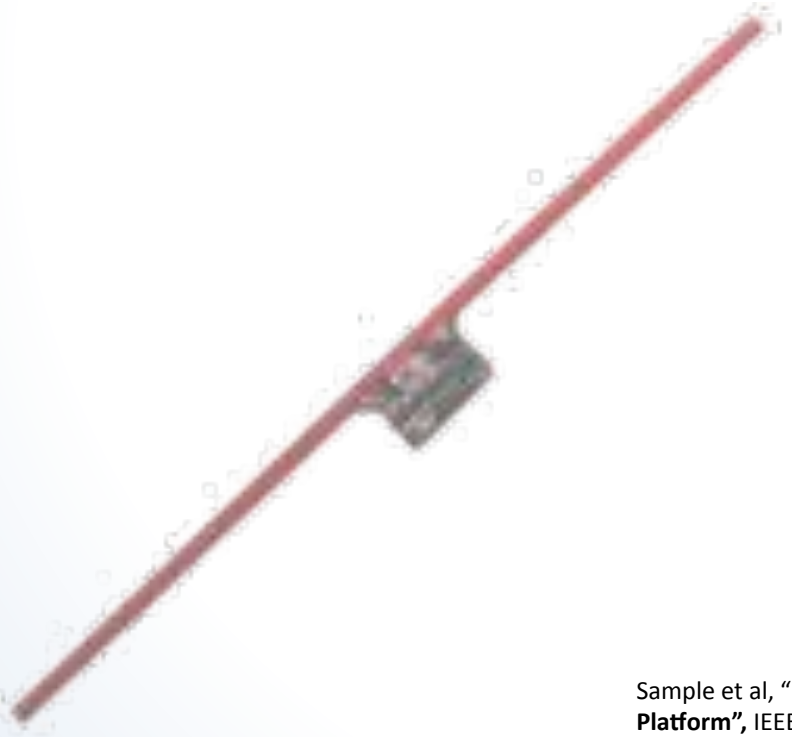
Tags transmit ASK or PSK via modulated backscatter

- Backscatter moves complexity from tag to reader

Readers for semi-passive tags need much better sensitivity due to longer range.

What's a WiSP?

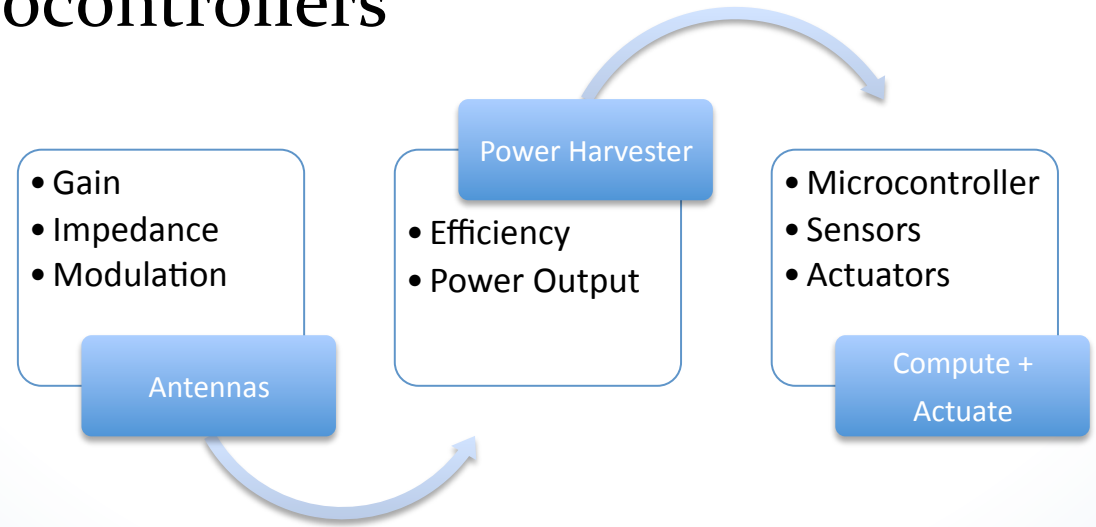
- Wireless Identification and Sensing Platform [Smith, 2005]
  - Concept: Passive RFID with a general purpose computing element
  - Applications: Sensing, crypto, protocol design, etc
  - Inexpensive prototyping of new RFID concepts



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.

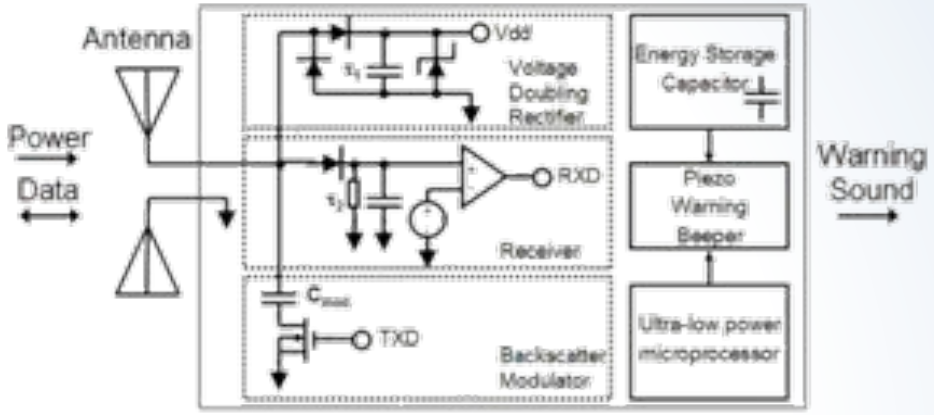
WiSPs at Duke

- 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

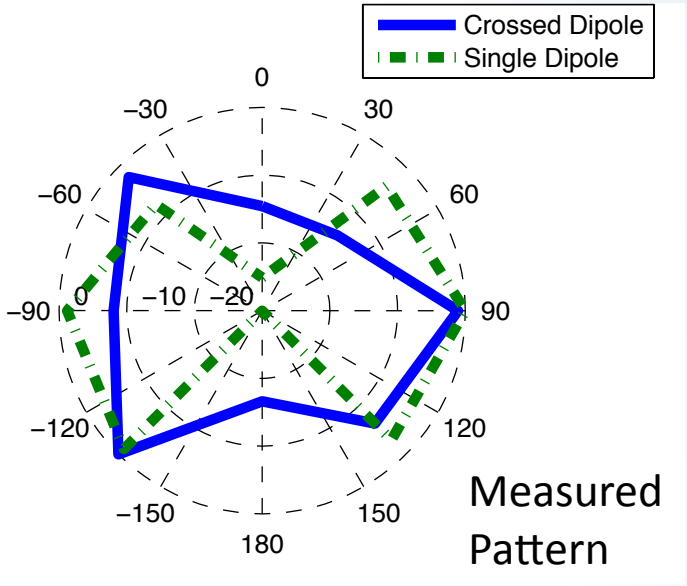
- WiSP + piezo actuator for construction site safety
- Reader mounted to heavy construction equipment
- WiSP in hard hat
- Passive operation allows unlimited lifetime- no batteries to fail

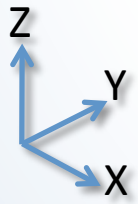


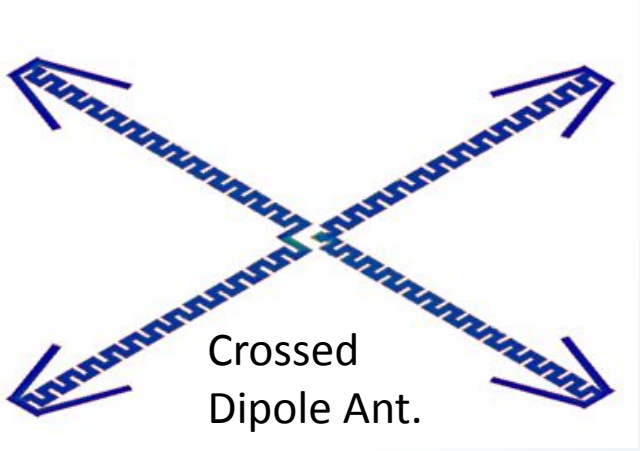
[Thomas, Teizer, Reynolds, 2010]

SmartHAT WiSP

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



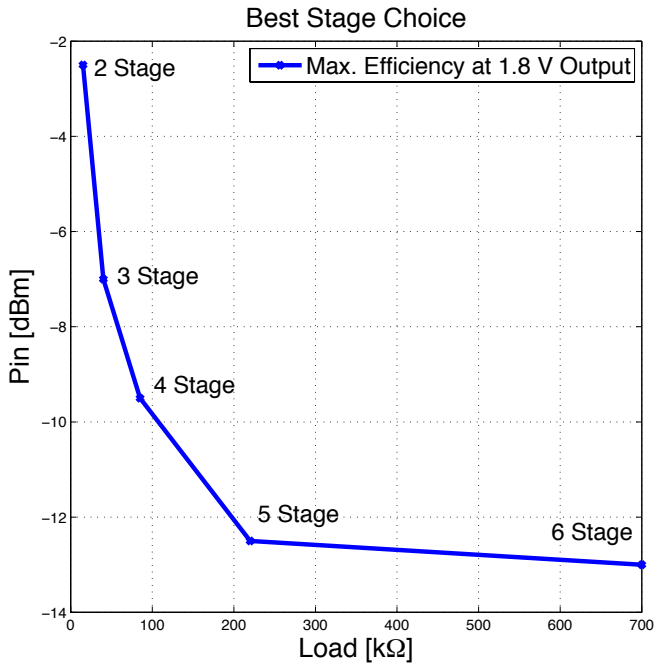




[Thomas, Teizer, Reynolds, 2010]

Power Harvesters are Nonlinear

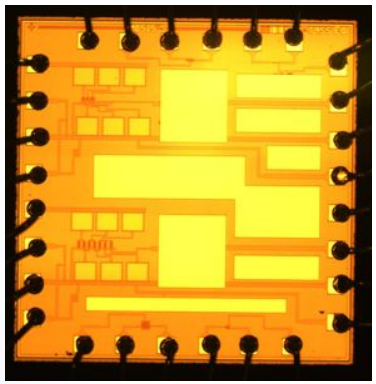
- Selecting operating point is critical in any RFID tag
- This is especially hard to do in a WiSP
  - Charging reservoir capacitor most of the time
  - Sleep current vs MCU current vs actuator current

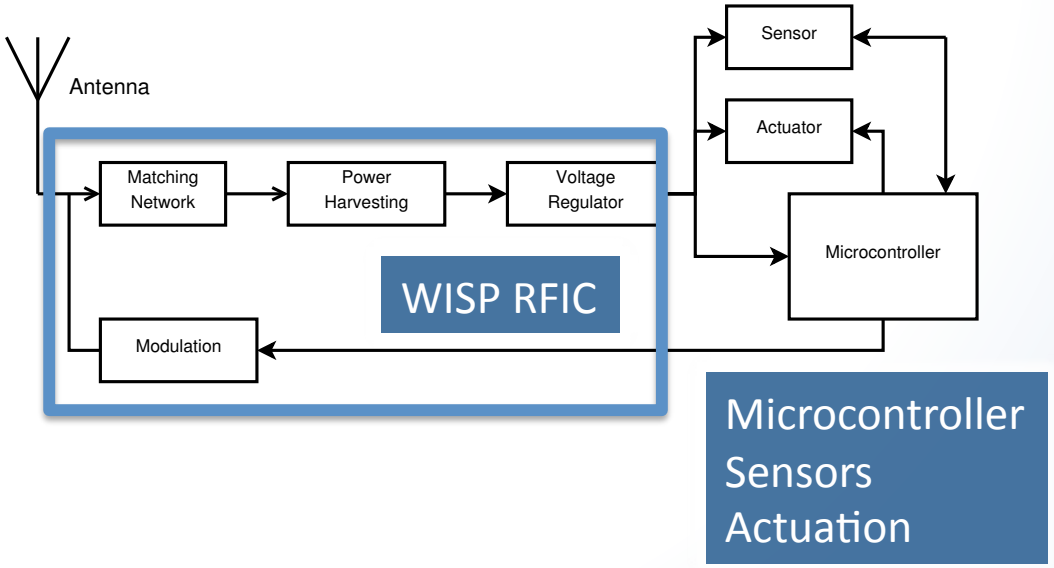


ADS simulations confirmed by measurement at 3,4,5 stages

WiSP Companion RFIC

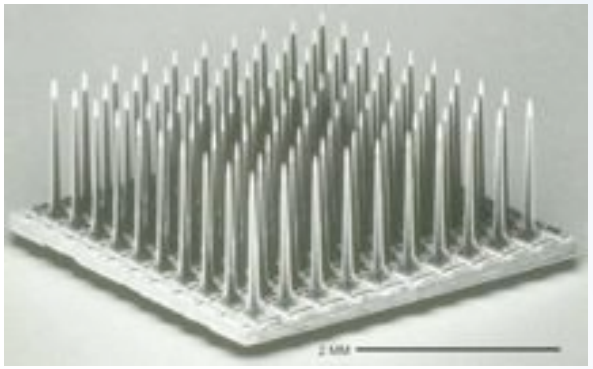
- MOSIS / AMI 0.5u-> 180nm Passive Analog Front End
- Support General Purpose Microcontroller: TI MSP430
  - Flexible protocol + sensor development
  - Extensive development tools
  - Partial Gen2 implementation available from Intel
- RFIC reduces WiSP complexity vs discrete AFE
- Include QAM backscatter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



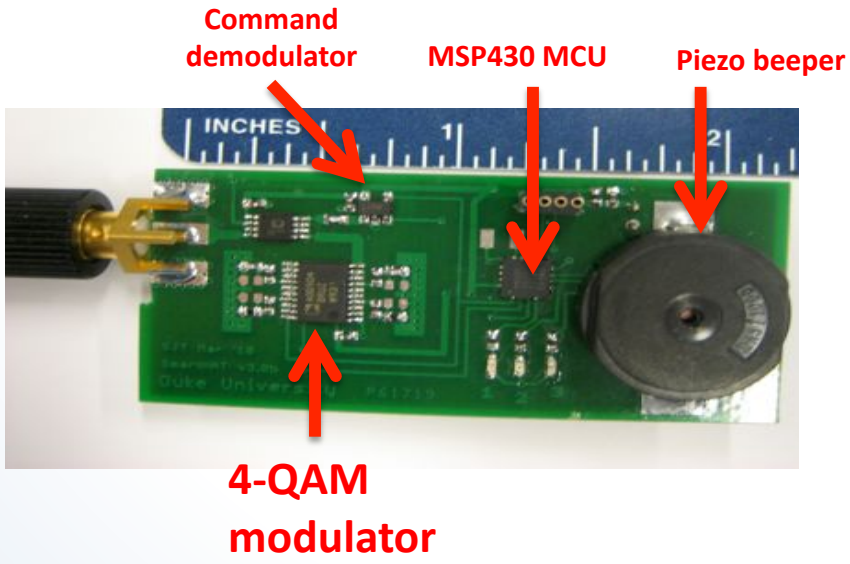


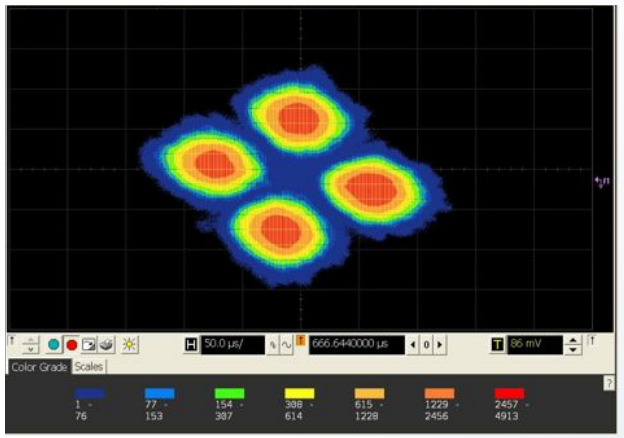
High-Speed Backscatter Links

- Today's RFID designed for small IDs or user memory blocks
  - Example: ISO18000-6c (Gen2)
  - ASK or PSK (2 states), Up to 640kbps
- Multi-state (QAM) backscatter sends multiple data bits per on-chip clock
  - Neurotelemetry arrays require a much faster link (> 5 Mbps)
  - QAM backscatter yields 2x to 4x power-bandwidth product improvement



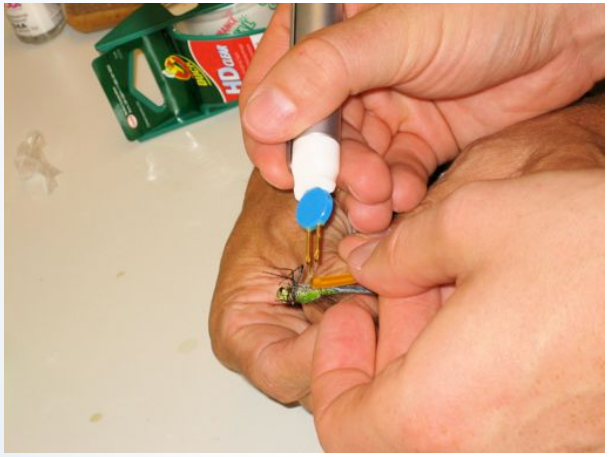
Utah Array Fig: Harrison, R.R., "The Design of Integrated Circuits to Observe Brain Activity," *Proceedings of the IEEE, vol.96, no.7, pp.1203-1216, July 2008*

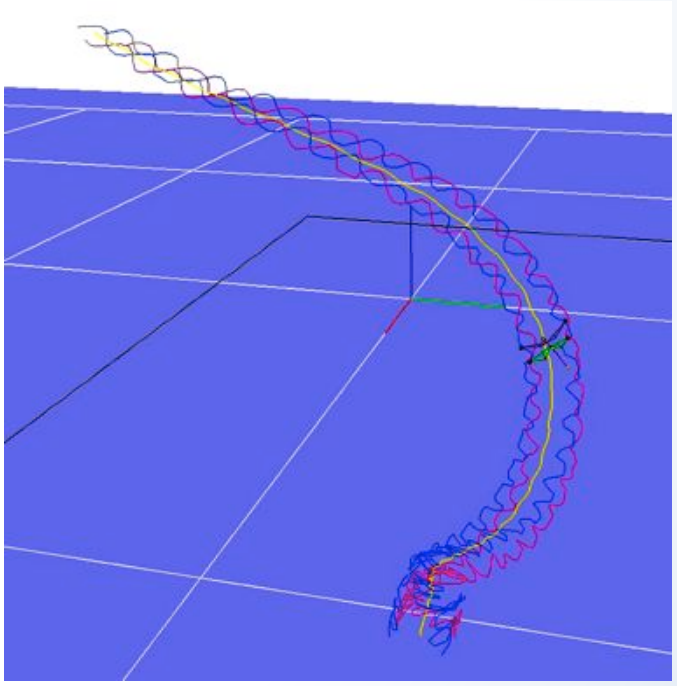




Labeling the World

- 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





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