Wireless Power Transfer and RF Energy Harvesting: New Options for System Designers

June 5, 2013
Stanford Computer Systems Colloquium

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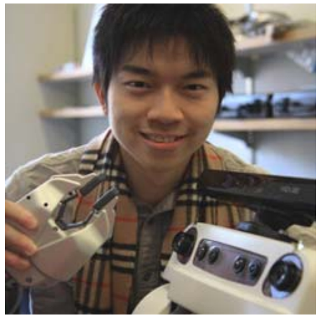
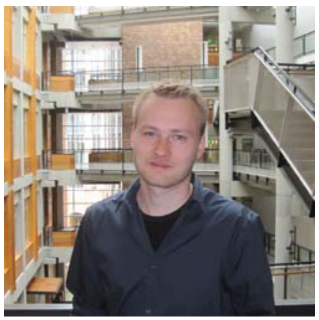


LT Jiang, ME

Ben Waters, EE

Vamsi Talla, EE



Artem Dementyev, EE

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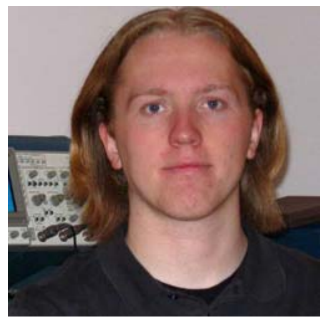

Aaron Parks, EE

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Alumni

Alanson Sample
(Postdoc)
Now Intel

Michael Buettner, CSE
(David Wetherall, co-advisor)
Now Google

Lillian Chang
(Postdoc)
Now Intel

Sensor Systems

Applications

Ubicomp
Medical
Robotics
Security

Interpretation

Pretouch Grasping

Power

WISP
WARP
WREL
FREE-D

Comms

Data hiding
ABC

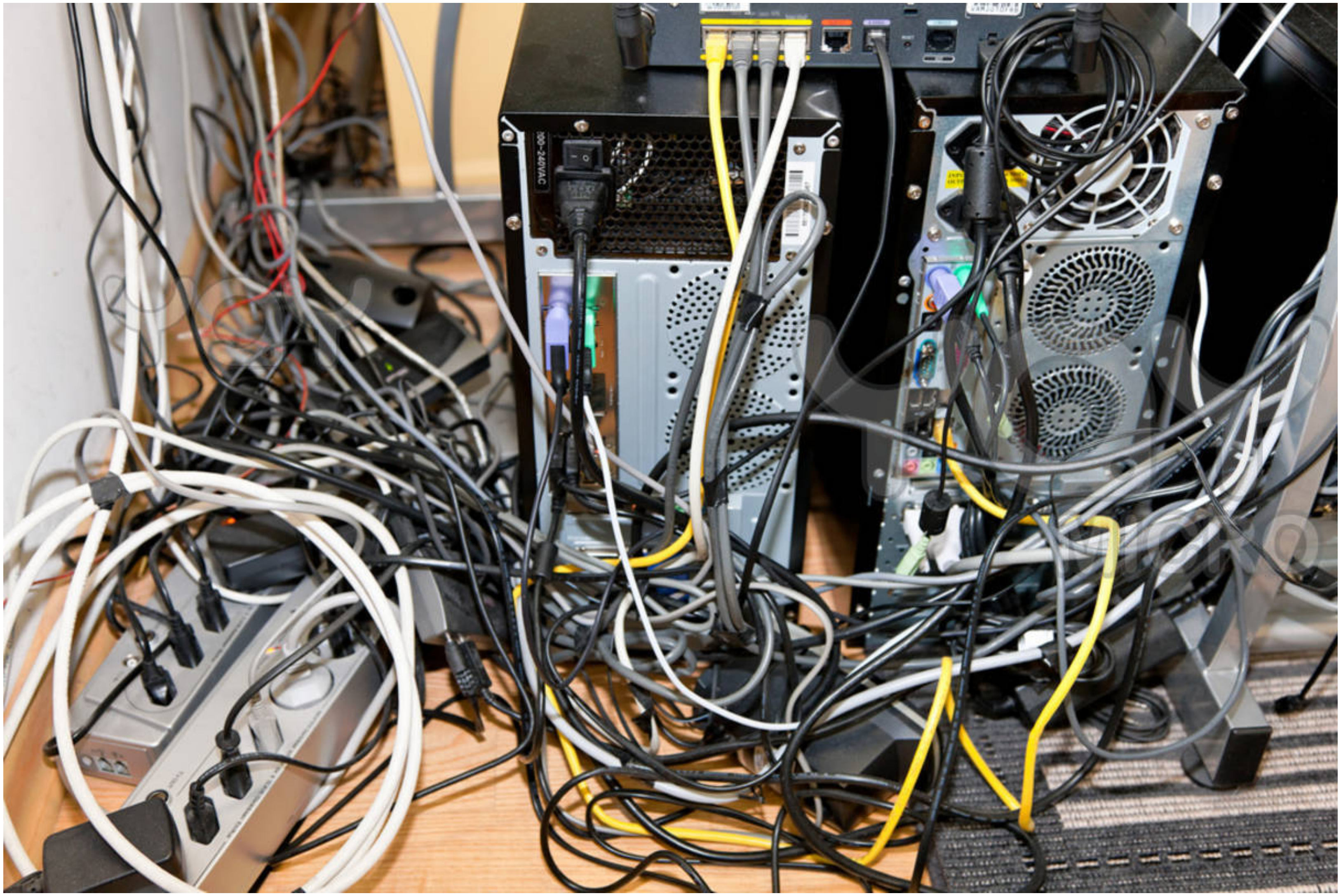
New sensors

E-Field Pretouch
Seashell Pretouch

Why Wireless Power?

Benefits of Wireless Power

Cord Elimination



Benefits of Wireless Power

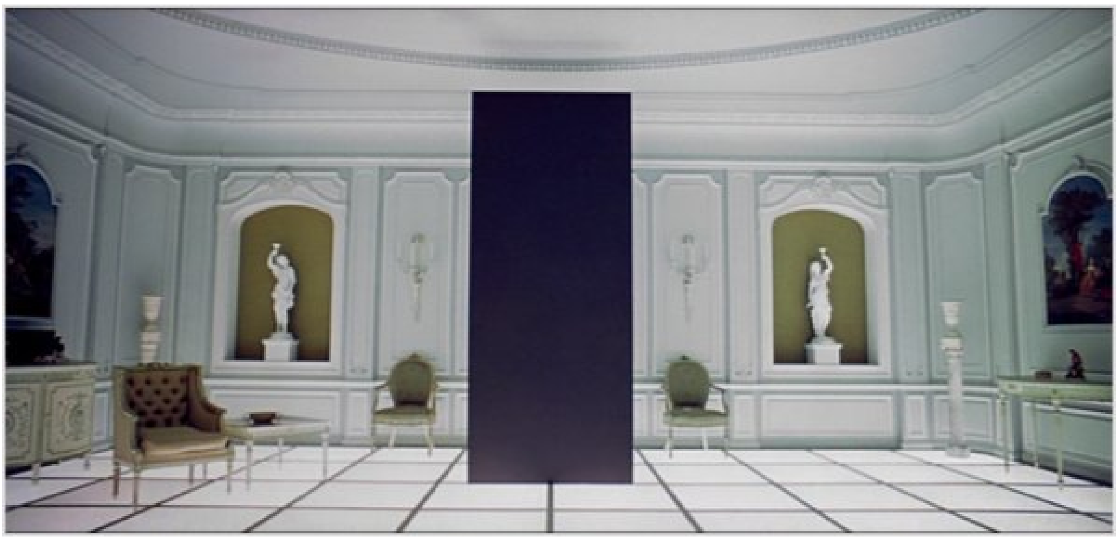
Battery Elimination

Lifetime --- Perpetual

Size

Weight

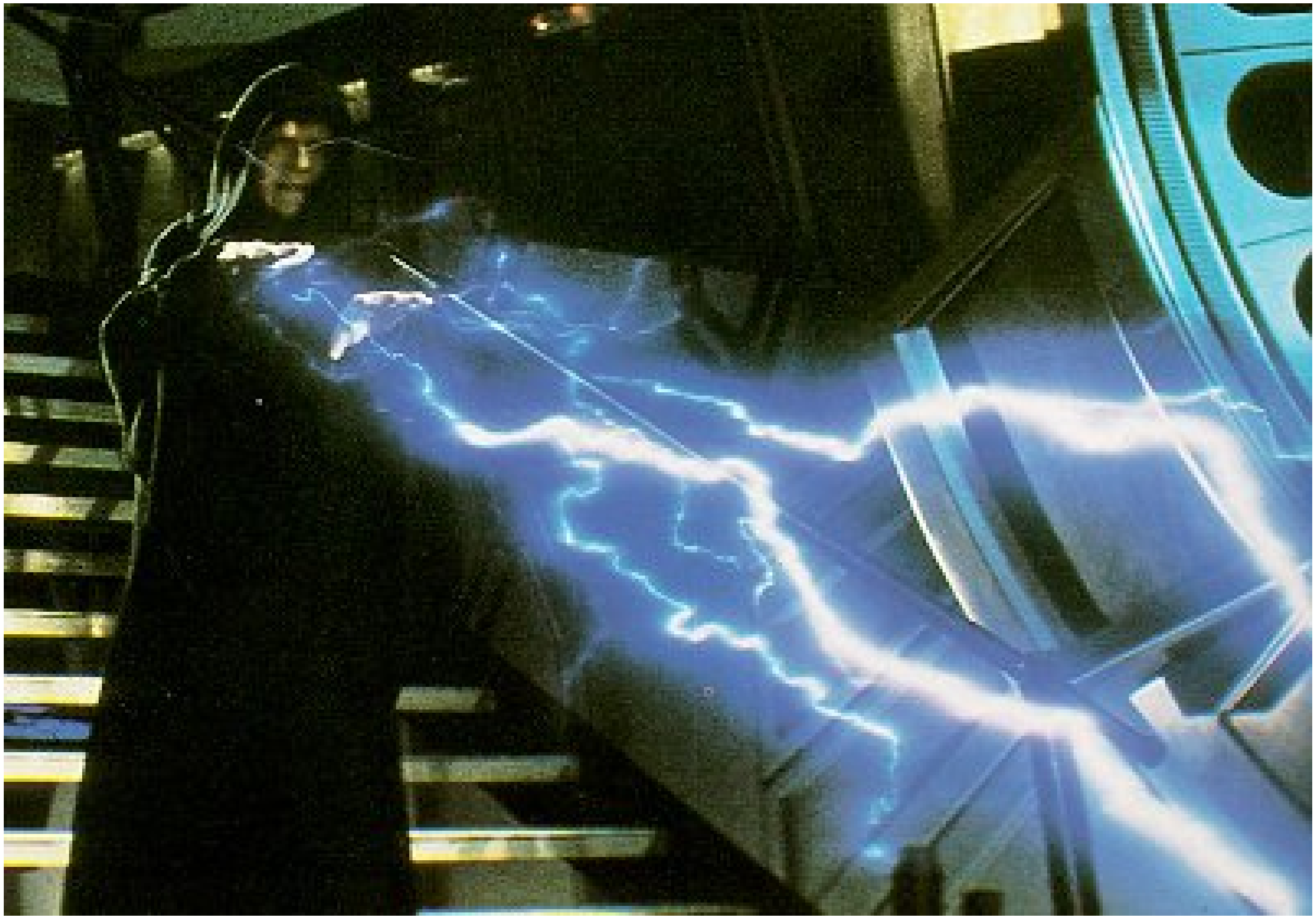
“Monolithic” technology



Connector elimination

Boundary integrity

Non-contact energy transfer

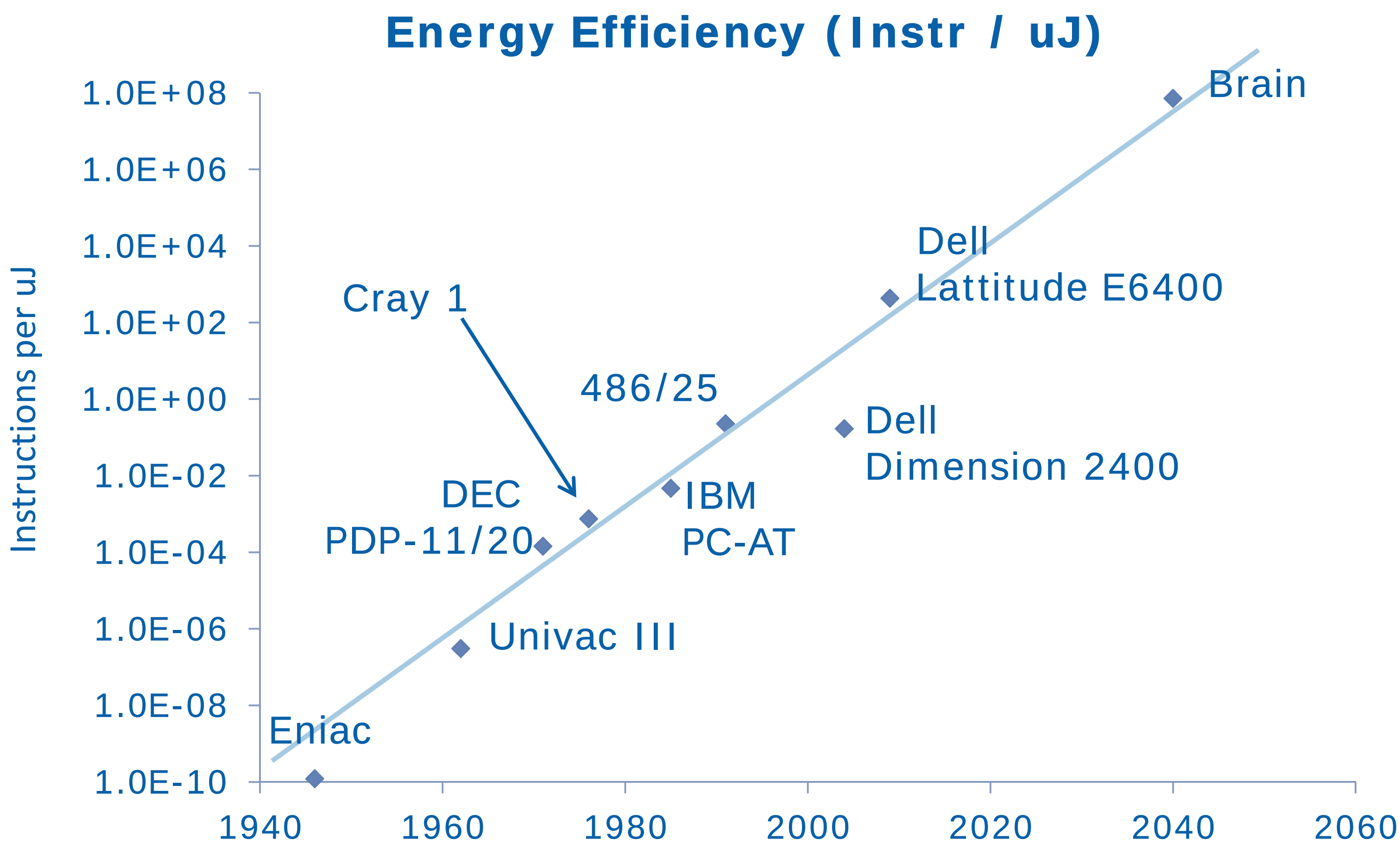


No Force required to make and break connections…nice in space!

The space of wirelessly powered systems

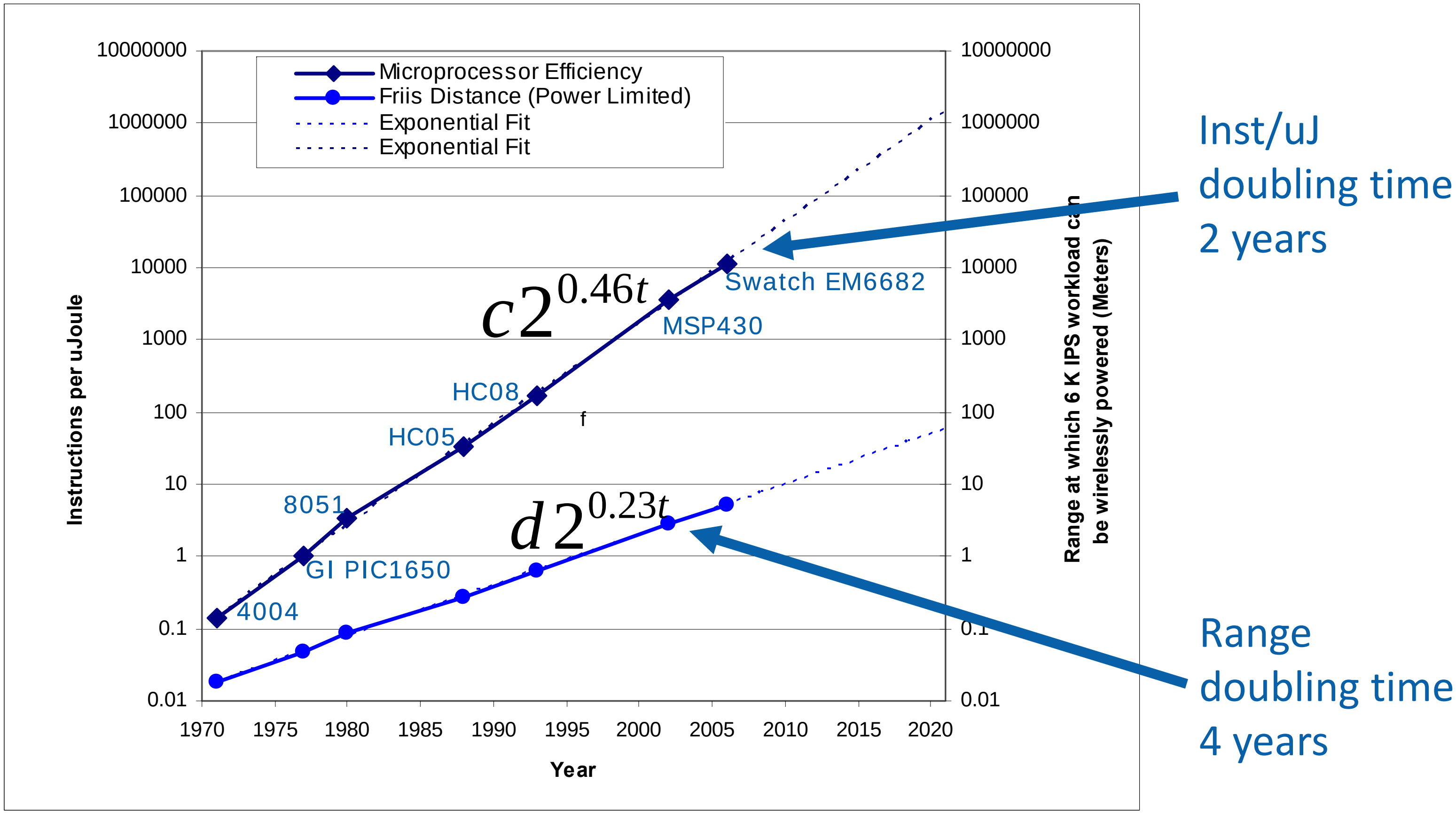
	Far field	Near field
Planted	**WISP**	**WREL** **FREED**
Wild	**WARP** **ABC**	**?**

Energy Efficiency Scaling



Data: ***Implications of Historical Trends in the Electrical Efficiency of Computing***
Koomey, Berard, Sanchez et al, IEEE Annals of the History of Computing, 2011

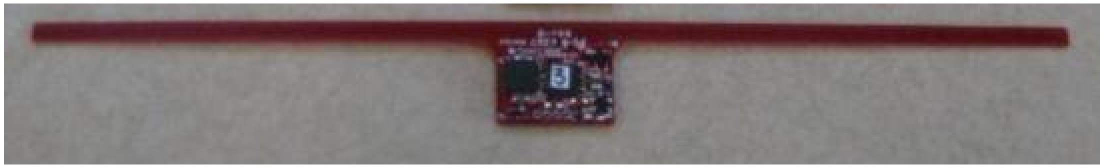
Range scaling of far field WPT

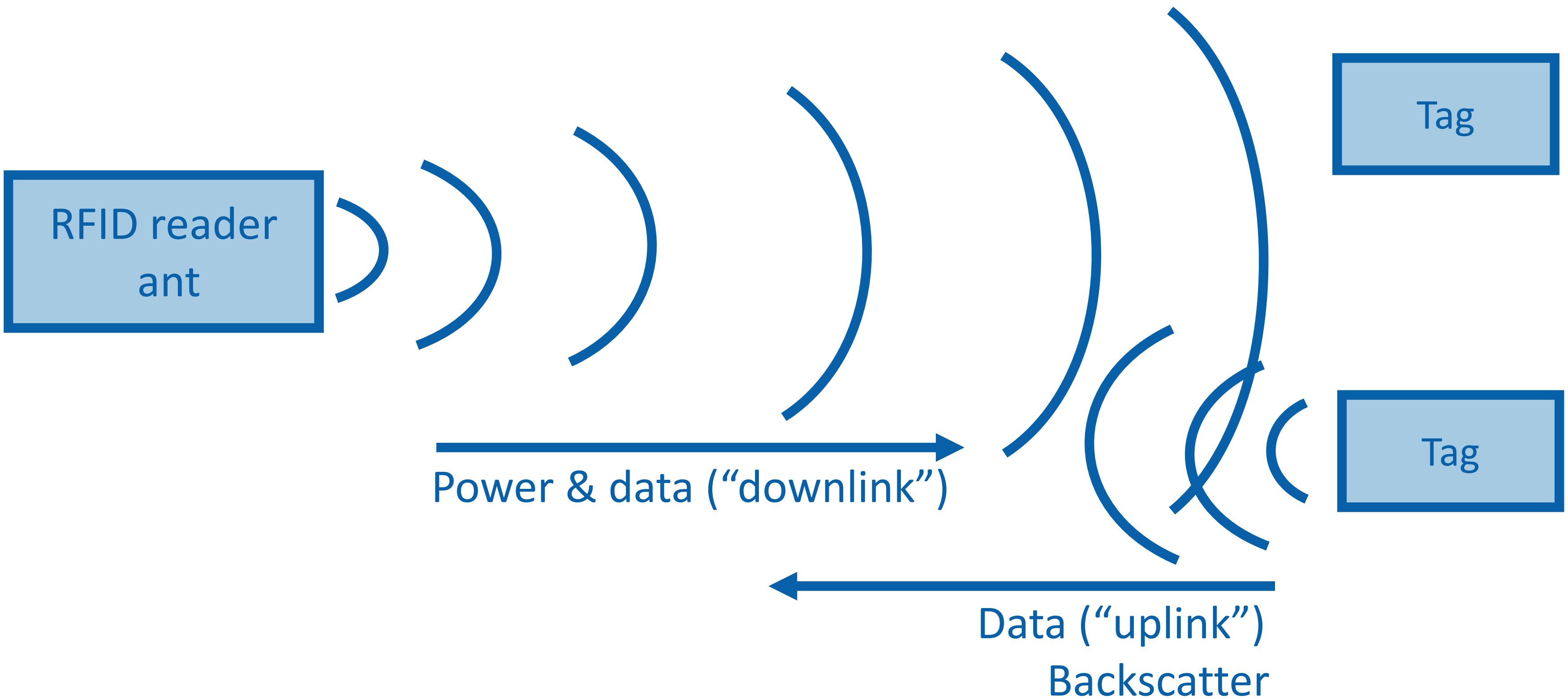


Range scaling of wirelessly powered sensor systems, J.R. Smith, in *Wirelessly Powered Sensor Networks and Computational RFID* J.R. Smith Ed., Springer 2013

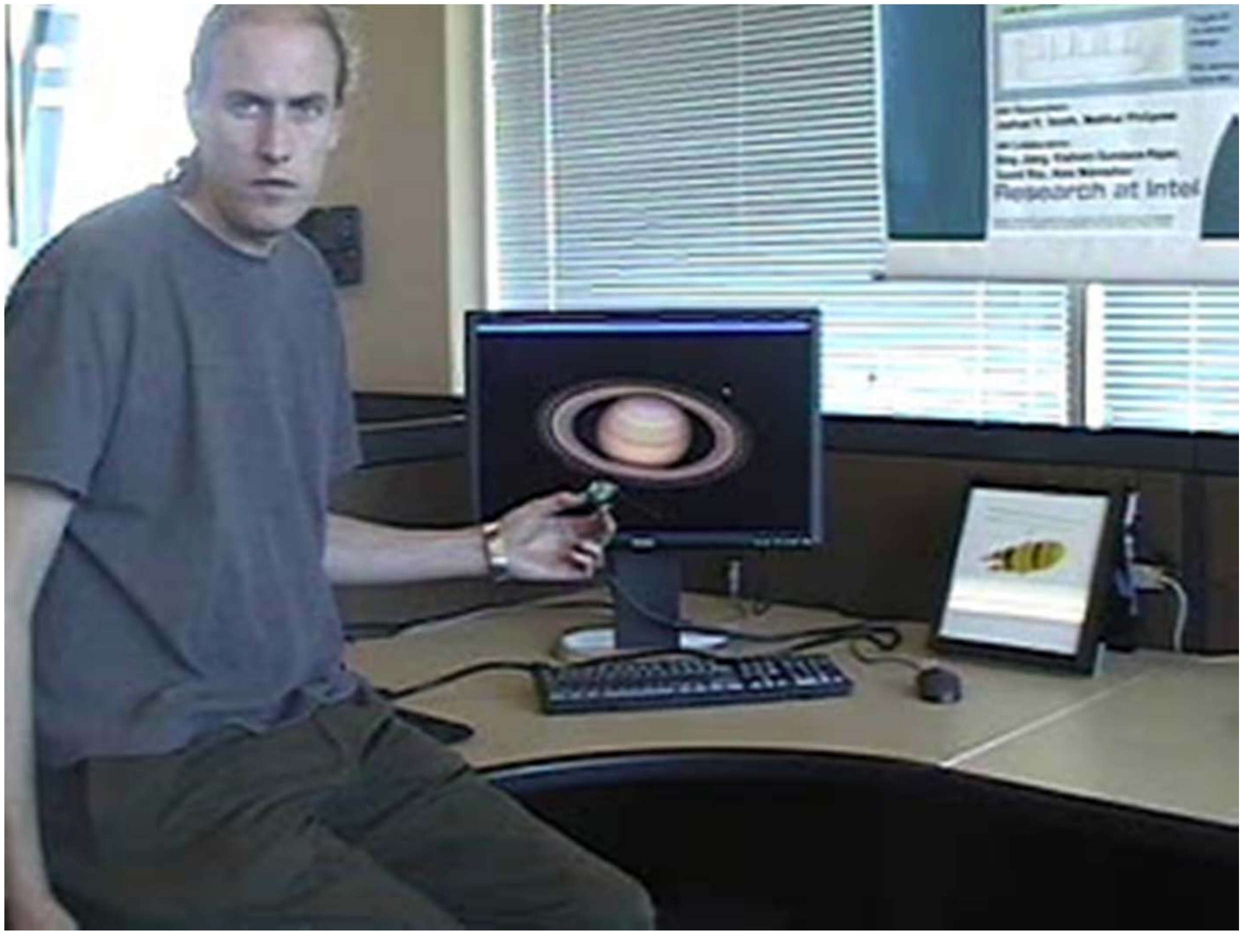
Development and Application of Wirelessly Powered Sensor Node, D. J. Yeager, UW MS Thesis

WISP & UHF RFID





WISP 3 Axis x 10 Bit Accelerometer

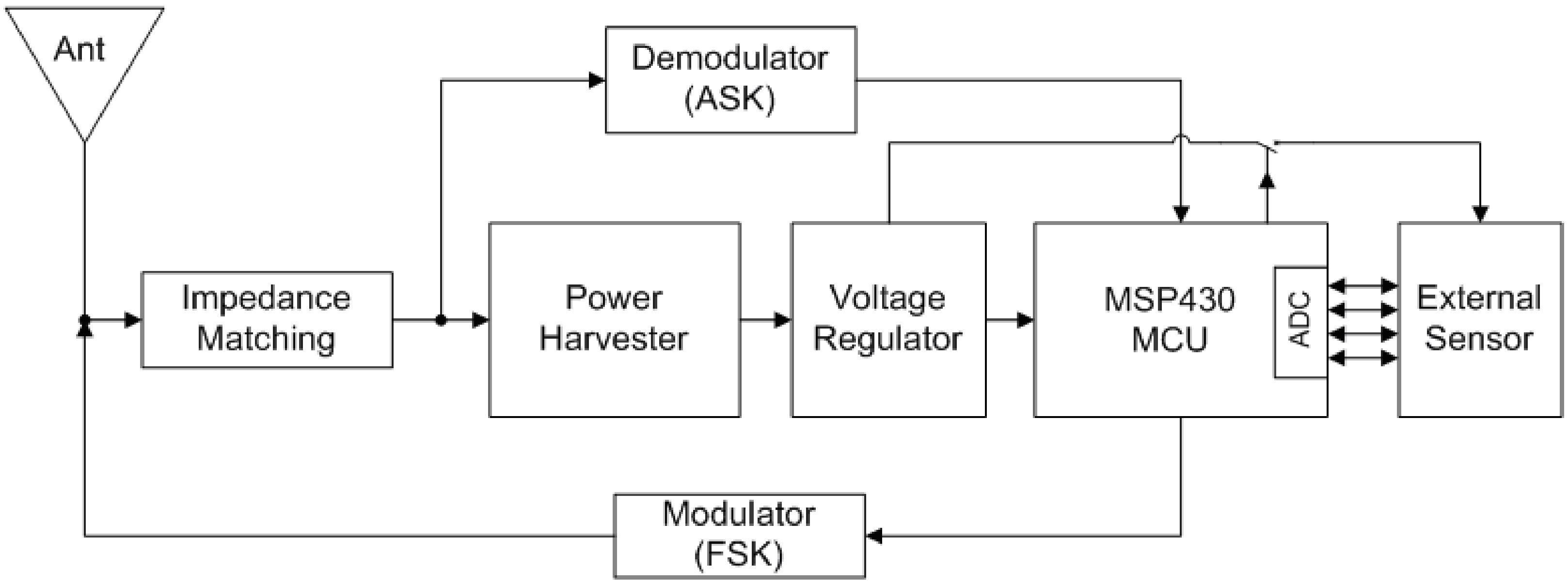


First UHF-powered accelerometer

A wirelessly powered platform for sensing and computation, J.R. Smith, A. Sample, P. Powledge, A. Mamishev, S. Roy. *Ubicomp 2006*

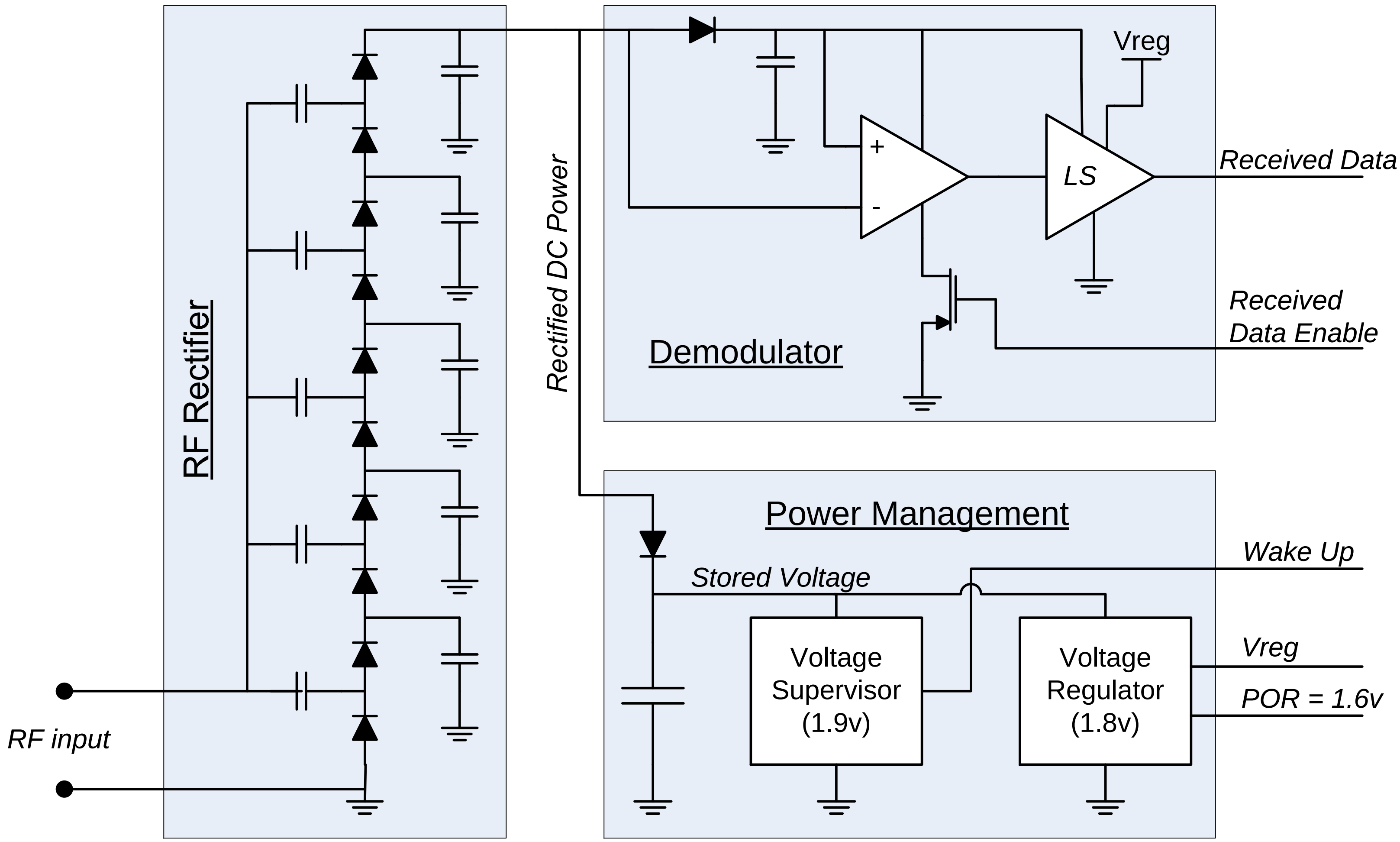
RFID Sensor Networks with the Intel WISP ***Winner Best Demo, Sensys 08,*** M. Buettner, B. Greenstein, R. Prasad, A. Sample, J.R. Smith, D. Yeager, D. Wetherall.

WISP Block Diagram

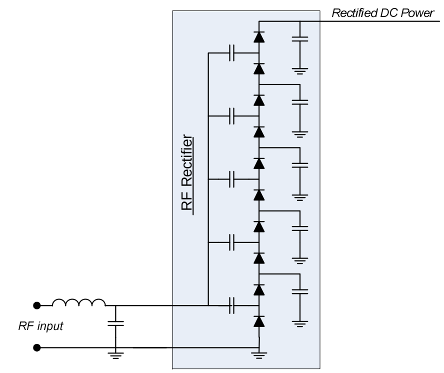


Design of an RFID-Based Battery-Free Programmable Sensing Platform, Alanson P. Sample, Daniel J. Yeager, Pauline S. Powledge, Alexander V. Mamishev, Joshua R. Smith. IEEE Transactions on Instrumentation and Measurement, Vol. 57, No. 11, Nov. 2008, pp. 2608-2615.

Analog Front End



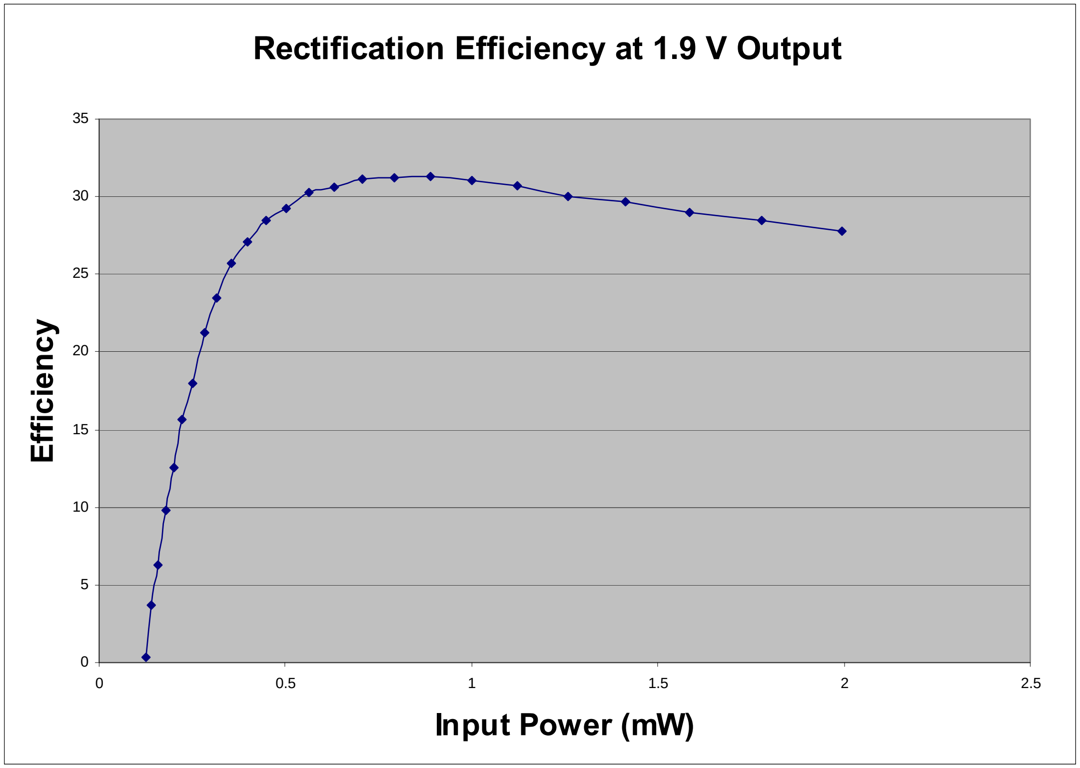
Rectifying Charge Pump (1 stage)



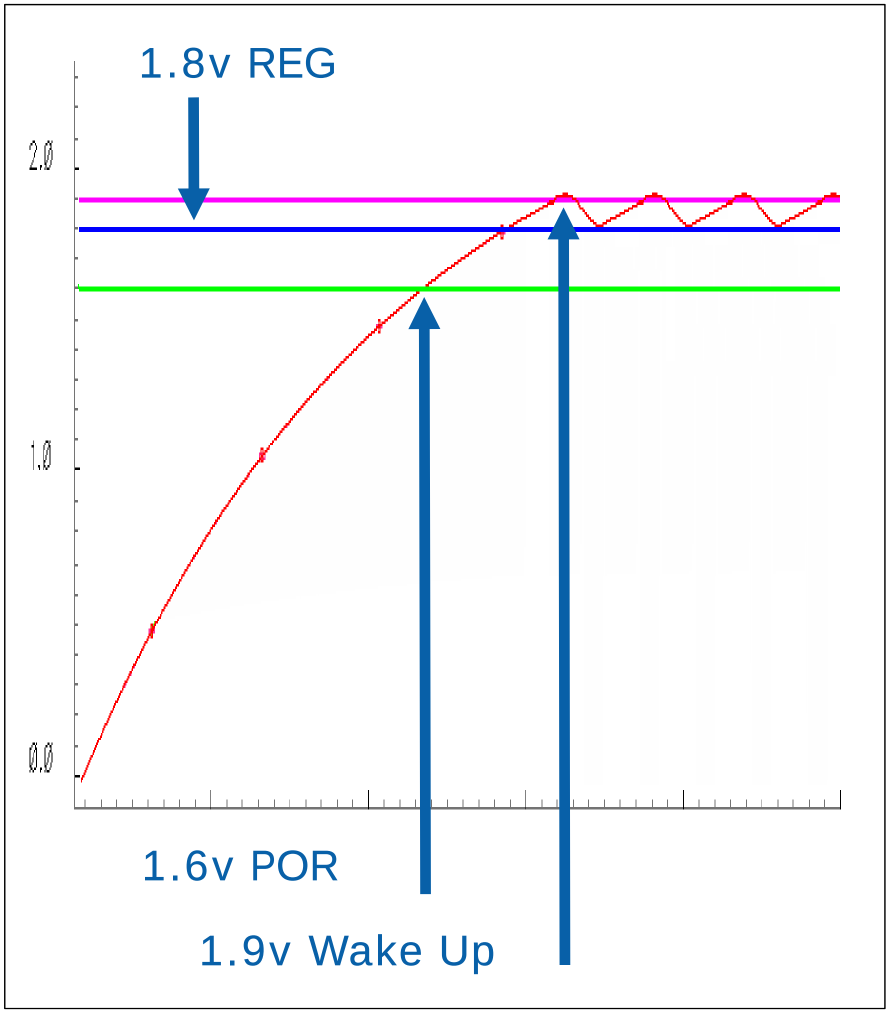
Rectifying Charge Pump (3 Stage)

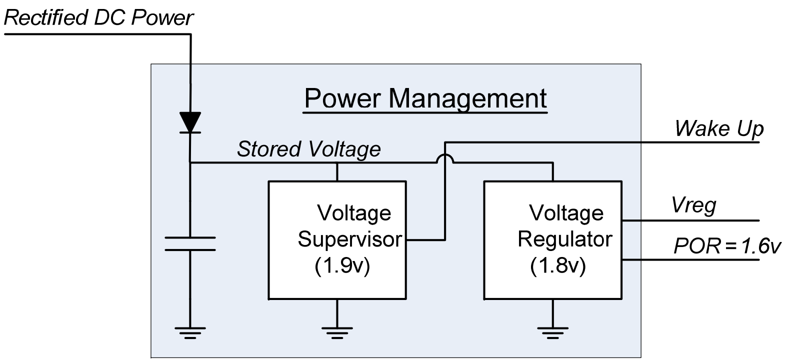
Rectifier Efficiency

Input and output impedance dependent



Power Management Block

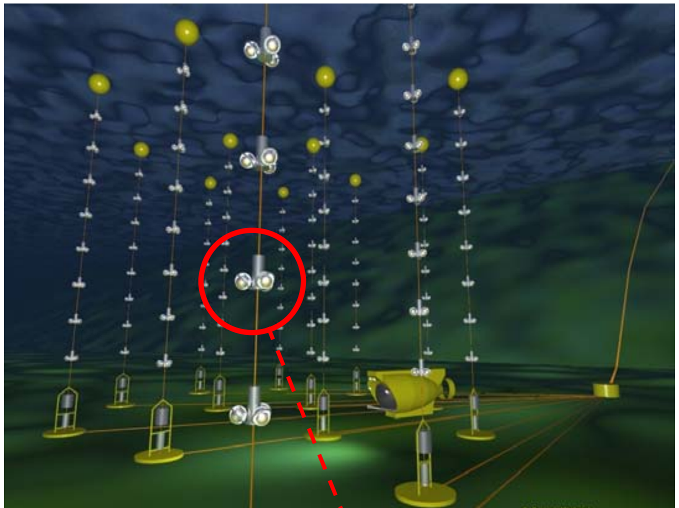


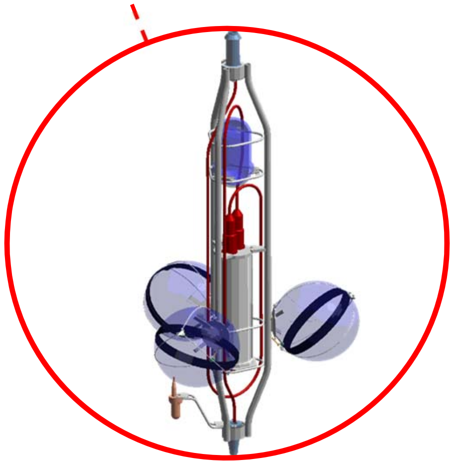


WISP Applications

WISP for Physical Oceanography in the The NEMO/Antares Neutrino Telescope

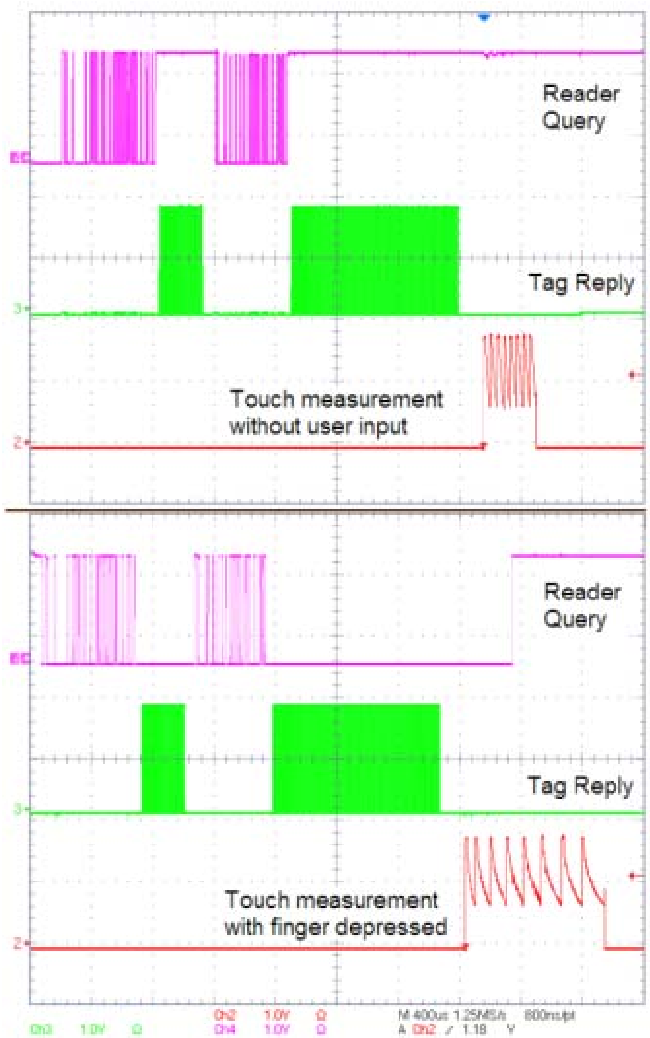
Luciano Trasatti,
INFN, Italy

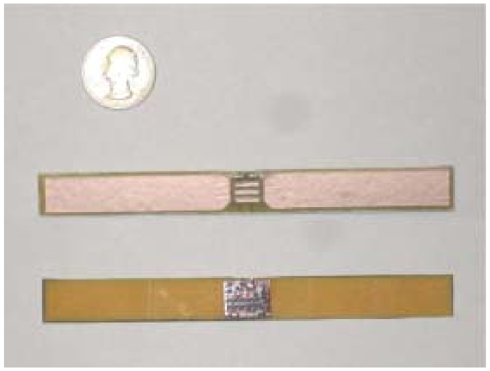


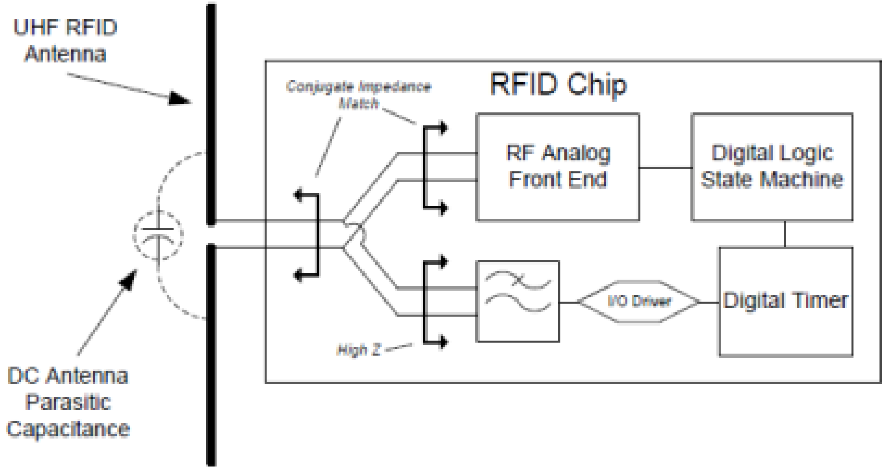


PORFIDO: An application of RFID to Oceanography, Trasatti, Cordelli, Habel, Martini, in *Wirelessly Powered Sensor Networks and Computational RFID,* J.R. Smith Ed., Springer 2013

Capacitive Touch WISP

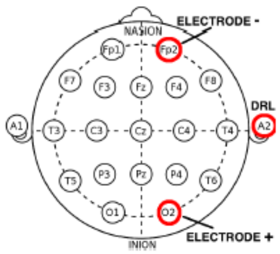


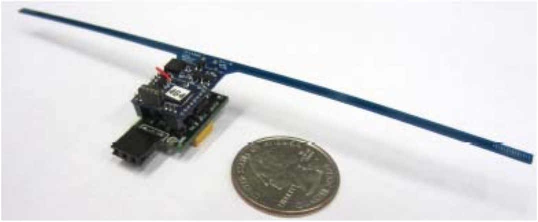


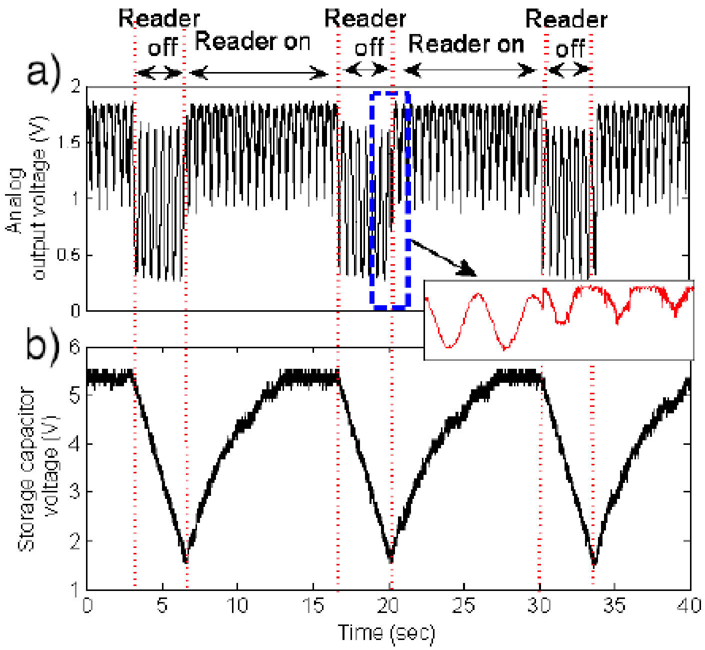


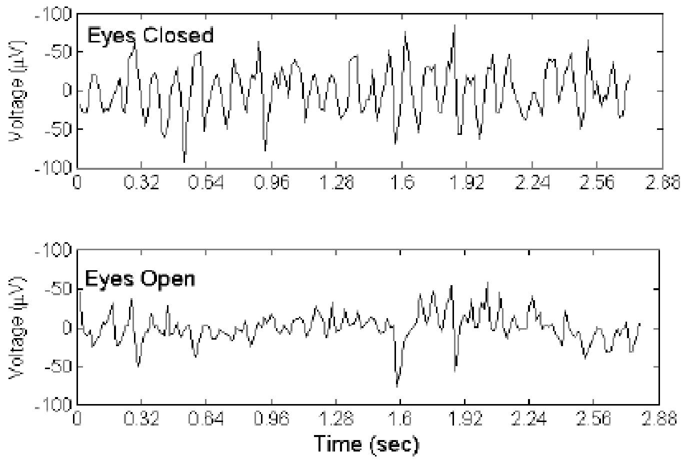
A Capacitive Touch Interface for Passive RFID Tags, IEEE RFID 2009, Alanson P. Sample, Daniel J. Yeager, Joshua R. Smith, ***Winner, Best Paper Award***

EEGWISP

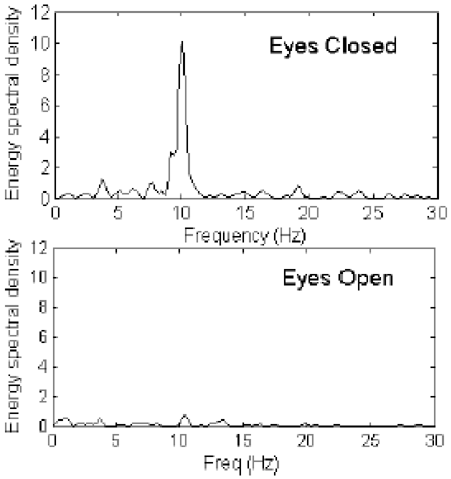








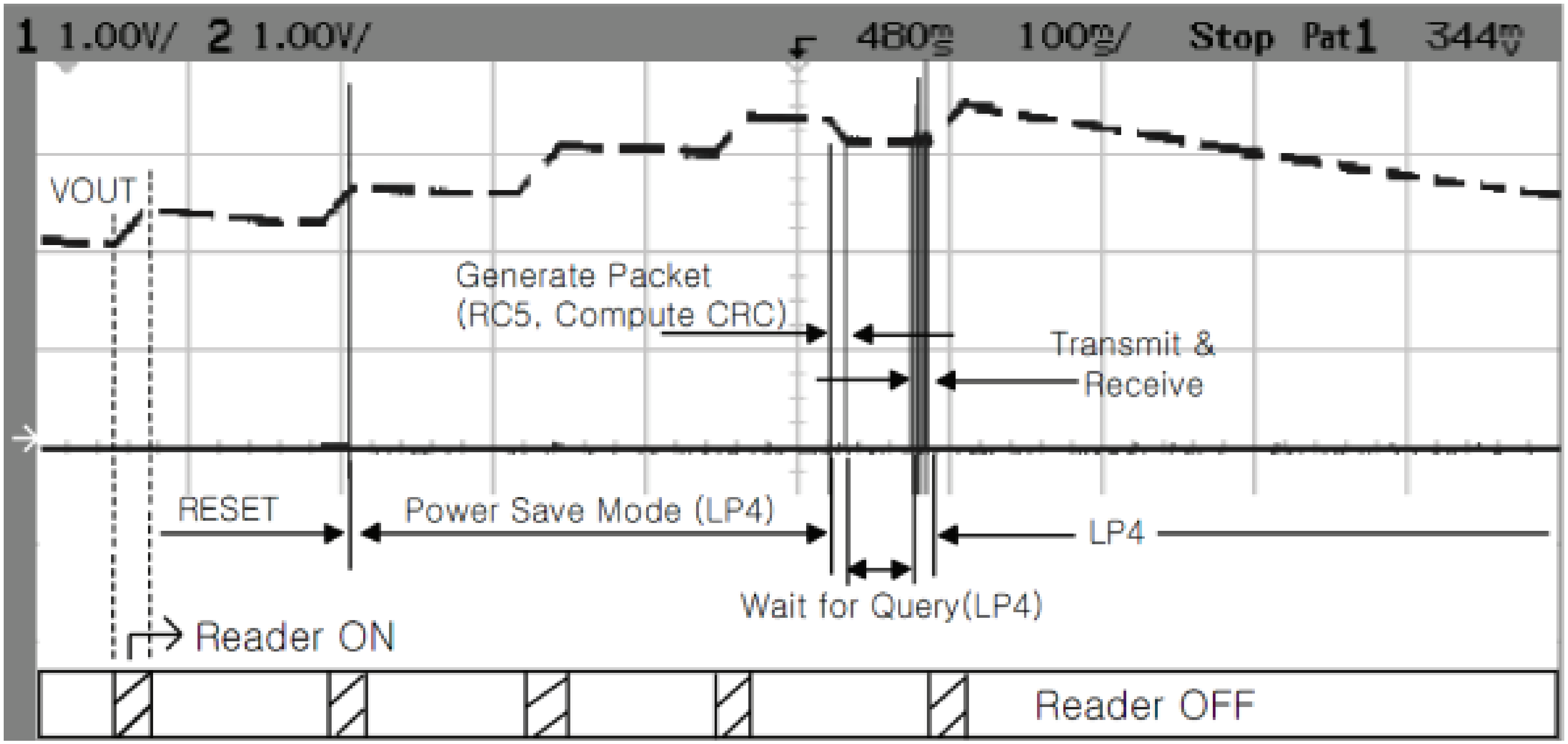
(b) Raw data



(c) Frequency content of the raw data in (b)

A Wearable UHF RFID-Based EEG System, Artem Dementyev and Joshua R. Smith, Proceedings of IEEE RFID, Orlando, Florida, April 2013.

RFID Cryptography



Strong RFID encryption (RC5)

Maximalist Cryptography and Computation on the WISP UHF RFID Tag, In Wirelessly Powered Sensor Networks and Computational RFID, J.R. Smith Ed., Springer 2013

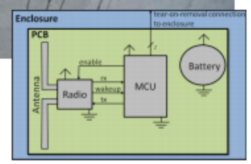
Commercialization: Intel BTAG

B.Tag Overview

BTAG is short for Brazil-Tag, and is a battery-assisted RFID Tag for use by the government of Brazil for Automatic Vehicle Identification (AVI). The tag supports a limited set of the EPC C1G2 RFID protocol, and the full SINIAV Protocol which is a superset to EPC C1G2

BTAG Mounted in Car

BTAG in Enclosure

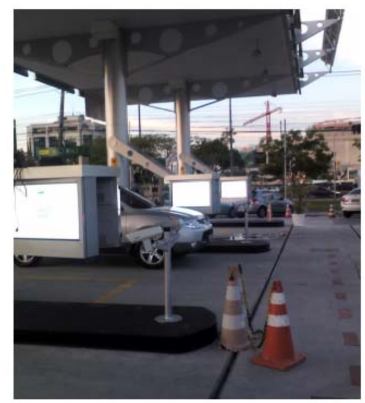


BTAG Architecture

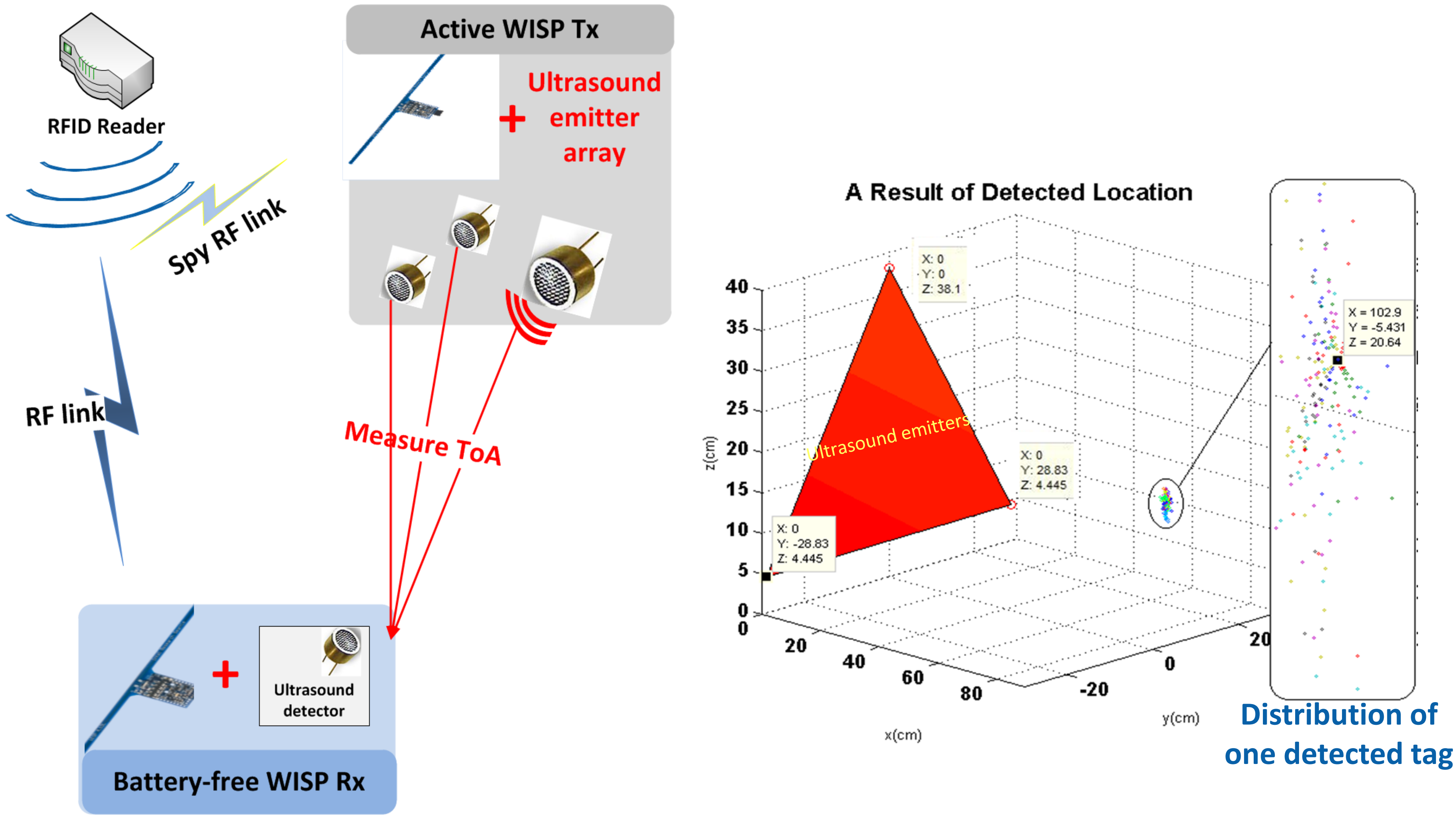
A key asset to the BTAG platform is its high level of security and cryptographic protection. This asset will allow extension of the BTAG platform described in this document to other potential "High-Security RF Identification" scenarios

Gas Station of the Future

- **BTAG is in the car and the readers are mounted over head**
- **Tag is read and car identified, displays at the pump show the customer deals and specials in the station**

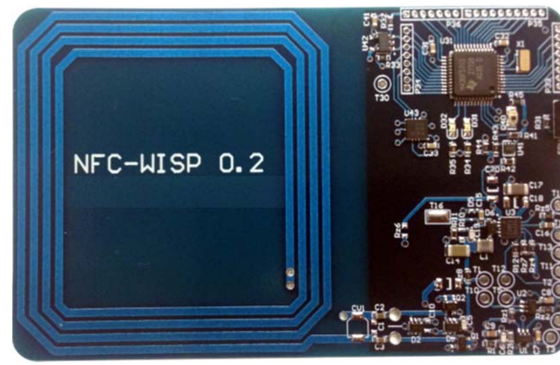


Ultrasonic Localization WISP --- ISTC



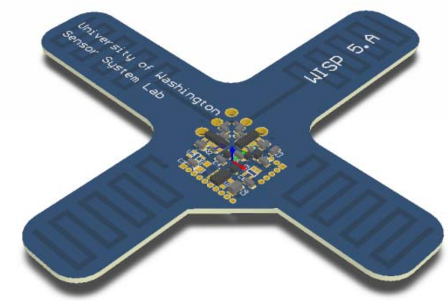
A battery-free RFID-based indoor acoustic localization platform, Yi Zhao and Joshua R. Smith, IEEE RFID, Orlando, Florida, April 2013.

Wirelessly powered bistable display



Wirelessly Powered Bistable Display Tags, A. Dementyev, A. Parks, J. Gummeson, D. Ganesan, J.R. Smith, A.P. Sample, To Appear, Ubicomp 2013

WISP 5.0 --- Available soon



WISP 4.1

4.3 meters range

Single antenna

3D accelerometer

MSP430 - F2272

- 16 MHz (max), 4MHz @ 1.8v
- 512B RAM
- 16K Flash
- Off Mode (LPM4) - 0.1 µA
- ADC / Timers / UART

WISP 5.0

9+ meters range*

Dual antennas

3D accelerometer

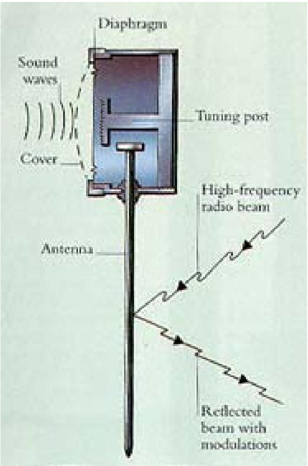
MSP430 - F5010

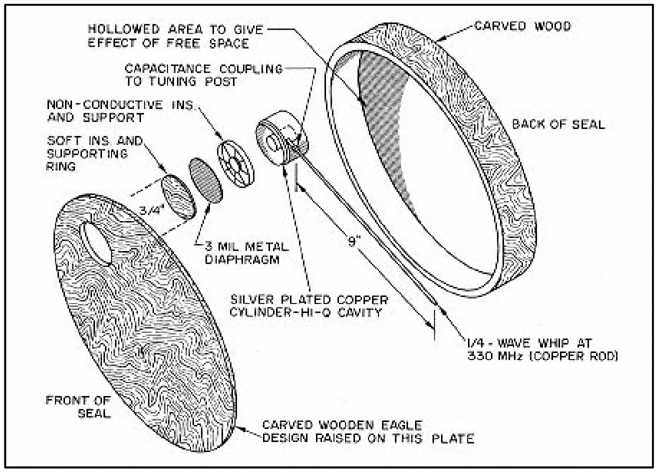
- 25 MHz (max), 8MHz @ 1.8v
- 6,144B Ram
- 16k Flash
- Off Mode (LPM4) - 1.1 µA
- ADC / Timers / UART

Analog Backscatter

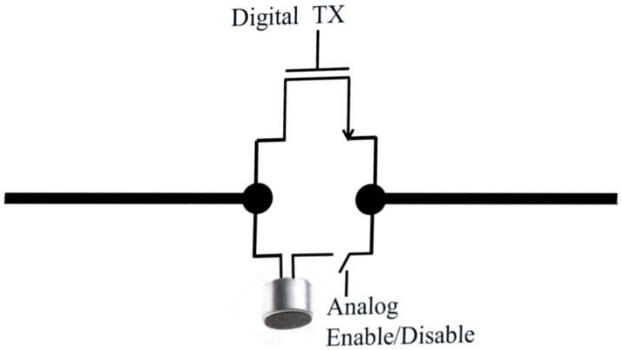
Hybrid analog-digital backscatter audio sensing

The Great Seal Bug aka “The Thing”, 1945





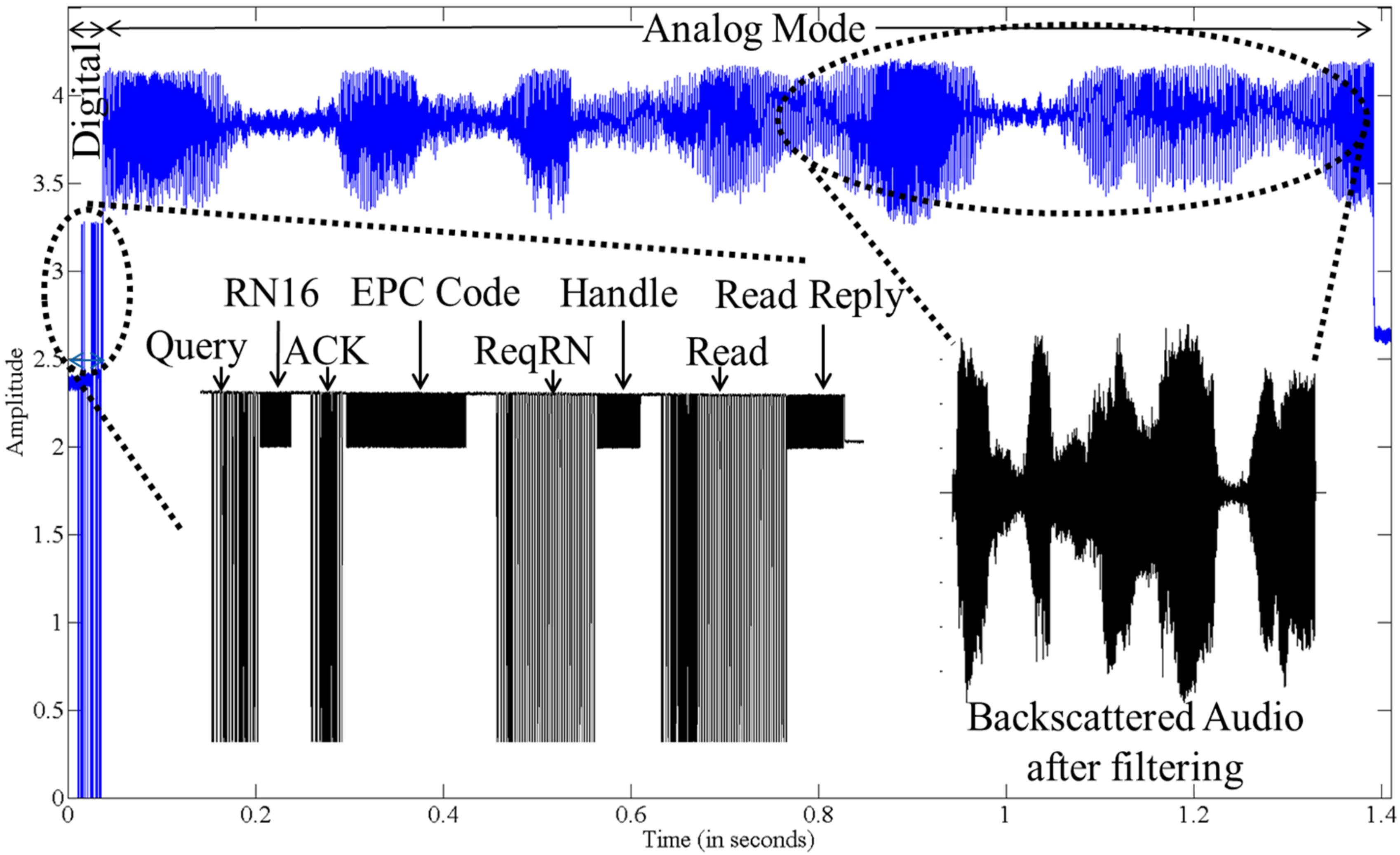
Hybrid Analog-Digital Zero-Power Mic, 2013



Hybrid Analog-Digital Backscatter: A New Approach for Battery-Free Sensing, V. Talla, J.R. Smith, IEEE RFID 2013. ***Nominated for best paper award***

Hybrid Analog-Digital Backscatter Platform for High Data Rate, Battery-Free Sensing, V. Talla, M. Buettner, D. Wetherall, J.R. Smith, WiSNET 2013 ***Winner best student paper award!***

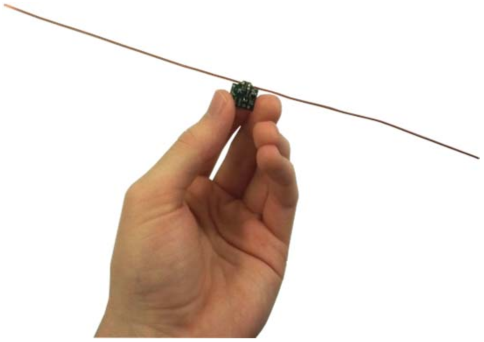
Results

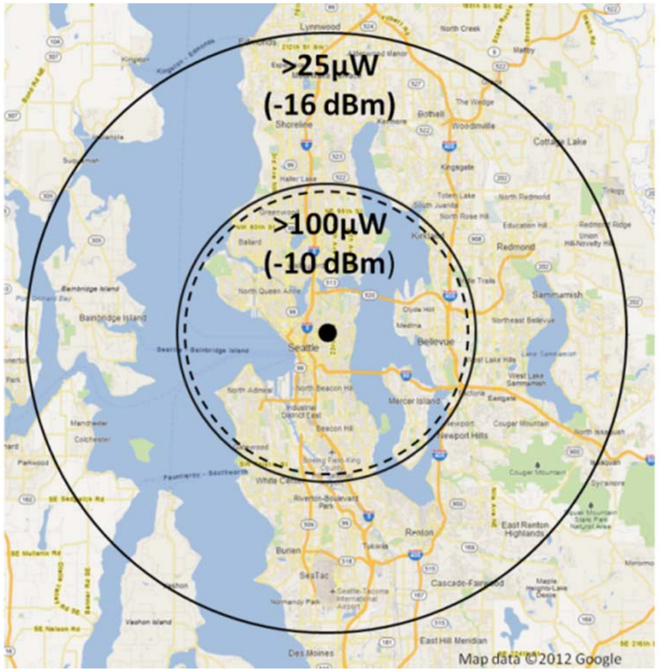


Analog Mode
Digital
RN16
EPC Code
Handle
Read Reply
Query
ACK
ReqRN
Read
Backscattered Audio after filtering
Amplitude
Time (in seconds)
0
0.5
1
1.5
2
2.5
3
3.5
4
0.2
0.4
0.6
0.8
1
1.2
1.4

WARP: Wireless Ambient Radio Power

WARP: Wireless Ambient Radio Power





Experimental results with two wireless power transfer systems, A.P. Sample and J.R. Smith, Proceedings RAWCON 2009

WARP: Cell Tower Power

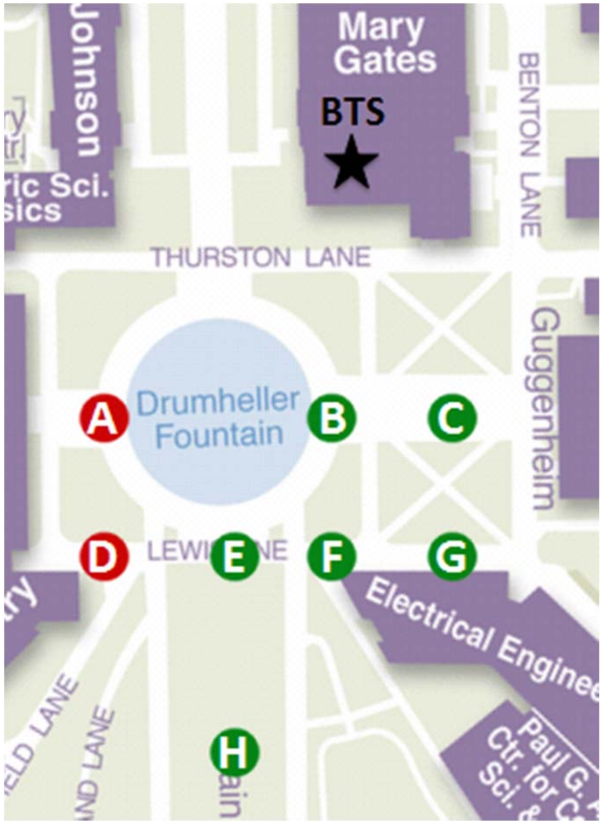
Mobile phone base transceiver station (BTS): 2.5 W to 640 W

Maximum observed operating range > **200m**

Each event is 275uJ Harvested ~ 1-3uW net

Location	Cycle Time (sec)
A	N/A
B	117.5
C	140
D	N/A
E	83.5
F	61
G	75
H	200

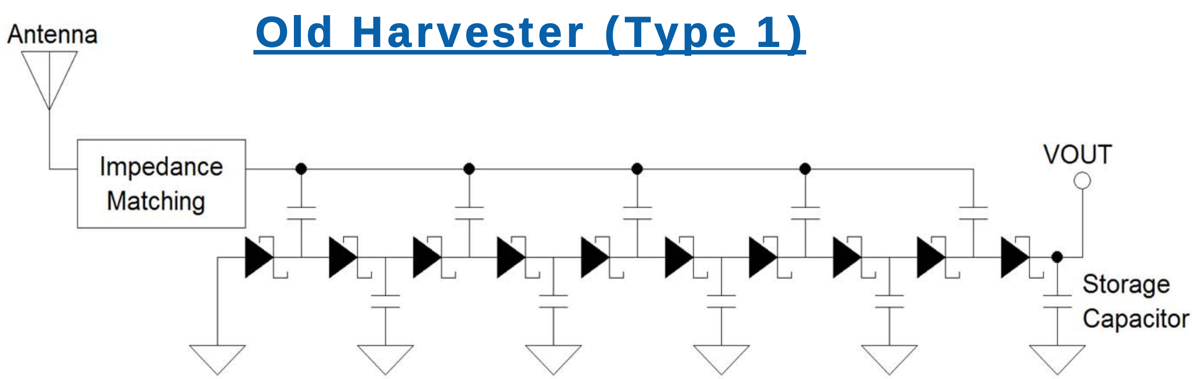
Experimental rig



Test locations around
Mary Gates Hall cell tower

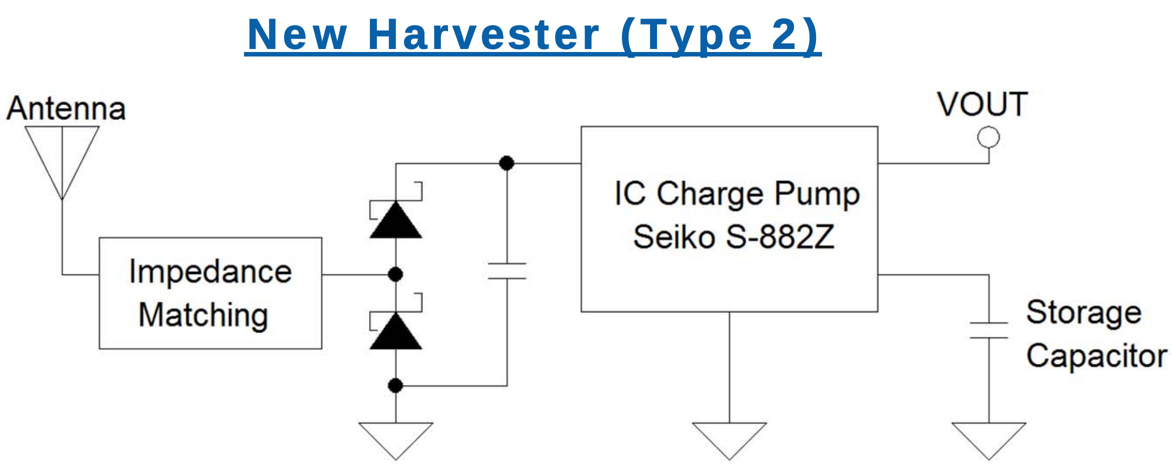
A Wireless Sensing Platform Utilizing Ambient RF Energy, Aaron Parks, Alanson Sample, Yi Zhao, Joshua R. Smith, WiSNET 2013

Old and new harvester designs



Efficient at "high" incident RF power

-9 dBm sensitivity (125 uW)

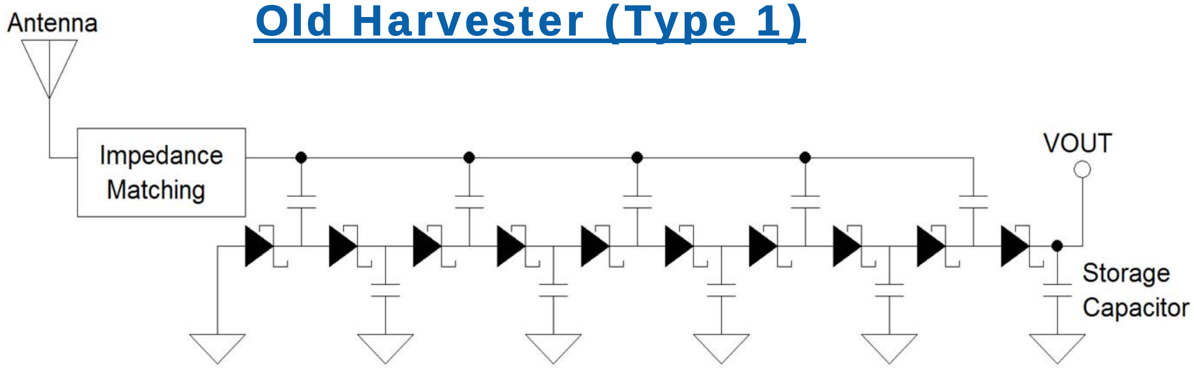


High sensitivity, at the expense of efficiency

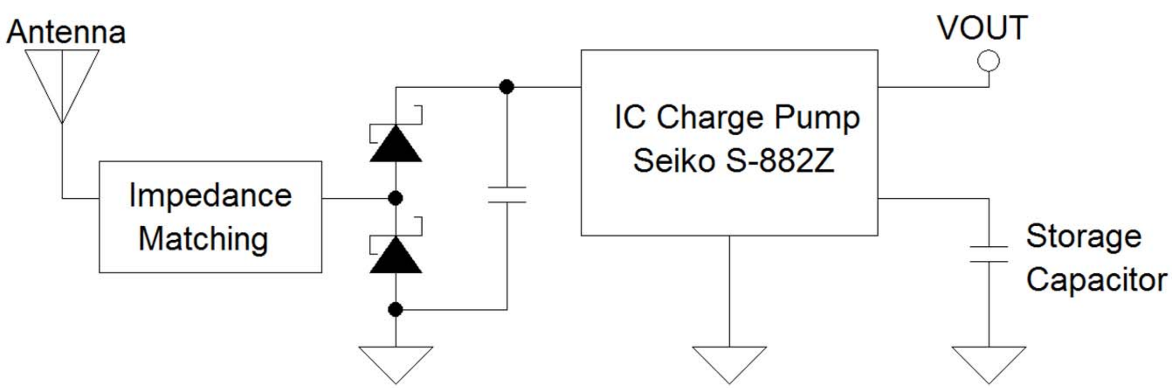
-18 dBm sensitivity (15.8 uW, almost 3x range improvement)

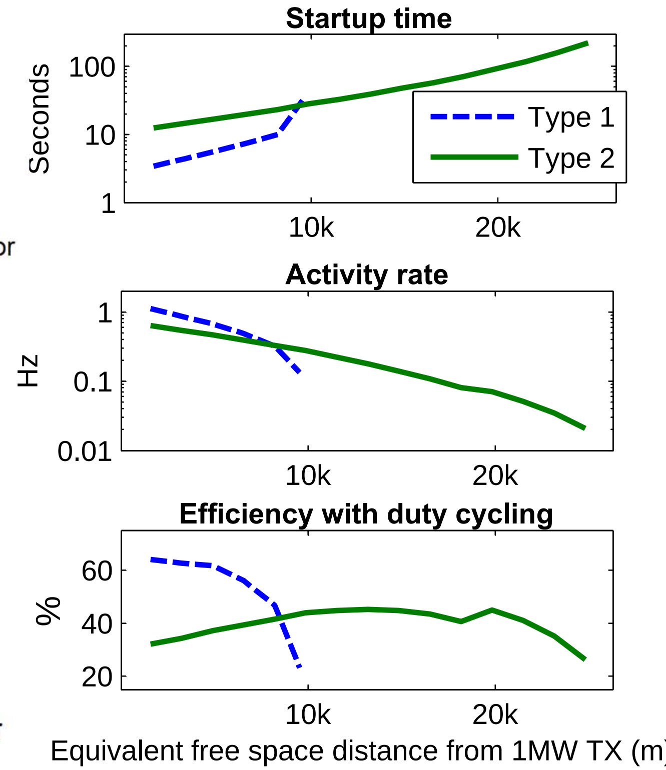
Old and new harvester designs

Old Harvester (Type 1)



New Harvester (Type 2)

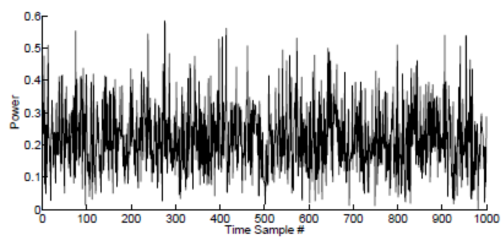




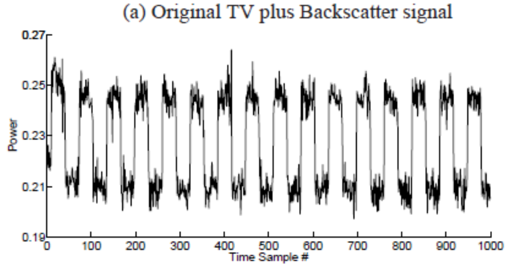
ABC: Ambient Backscatter Communication

ABC: Ambient Backscatter Communication

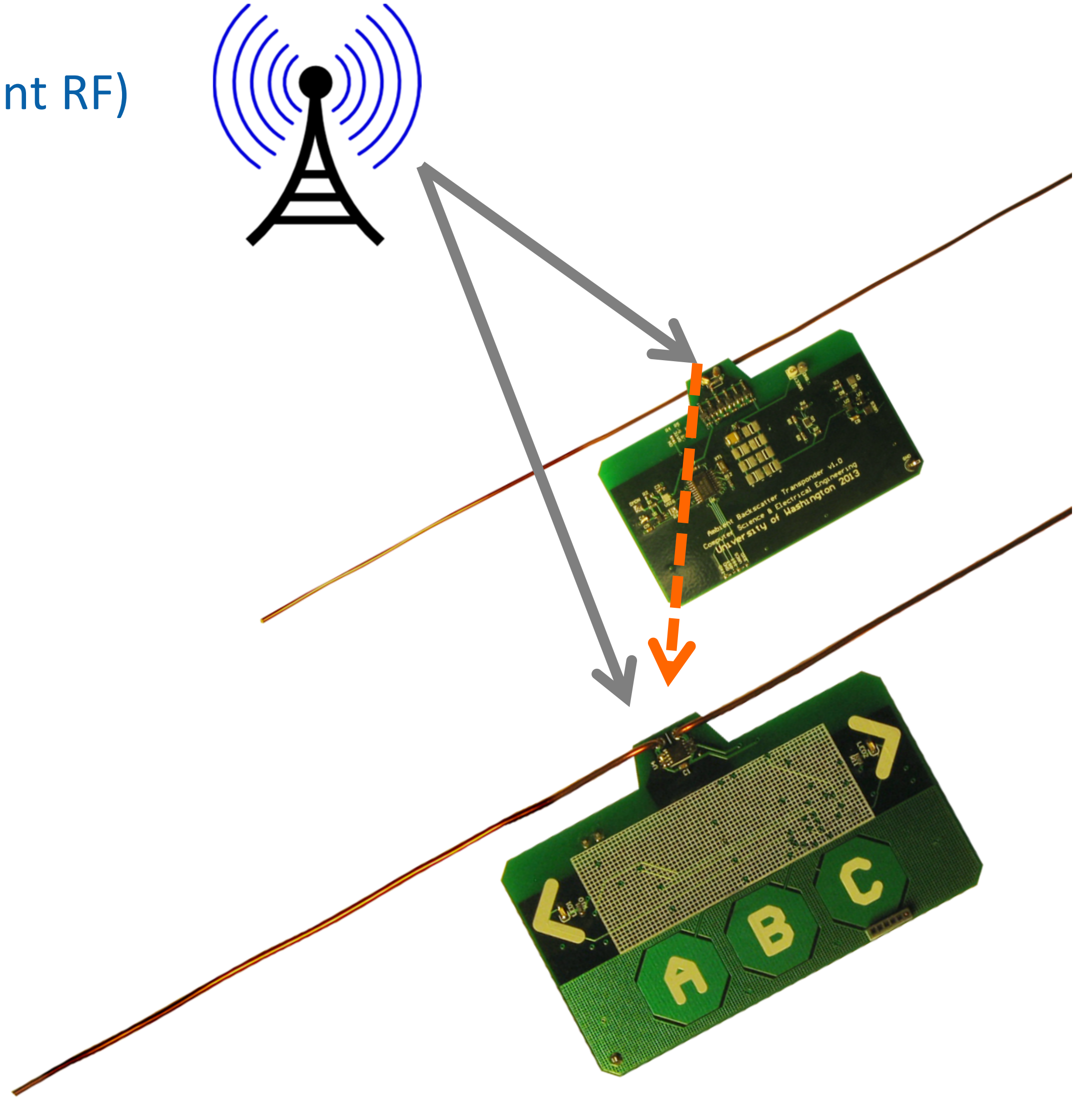
WISP (backscatter) x WARP (ambient RF)
Or, "RFID with no RFID reader"



(a) Original TV plus Backscatter signal

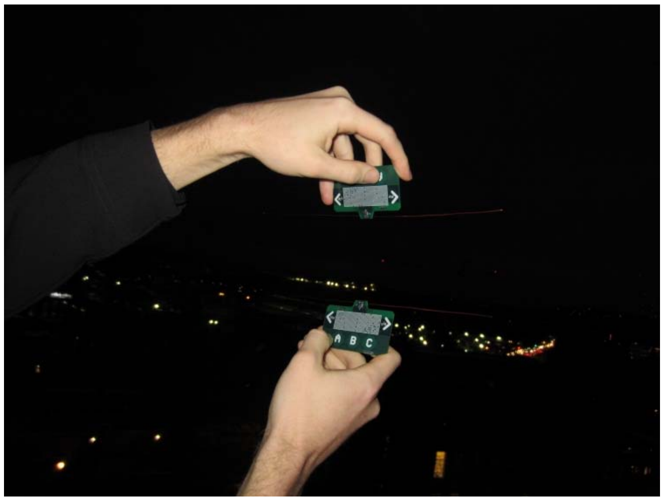


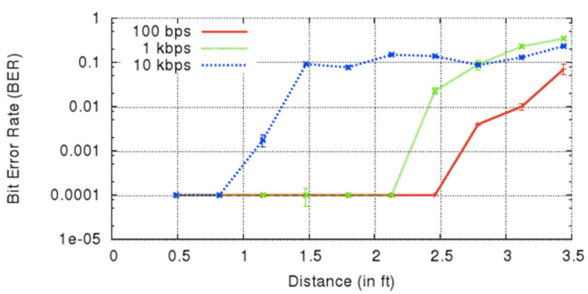
(b) Signal After Averaging



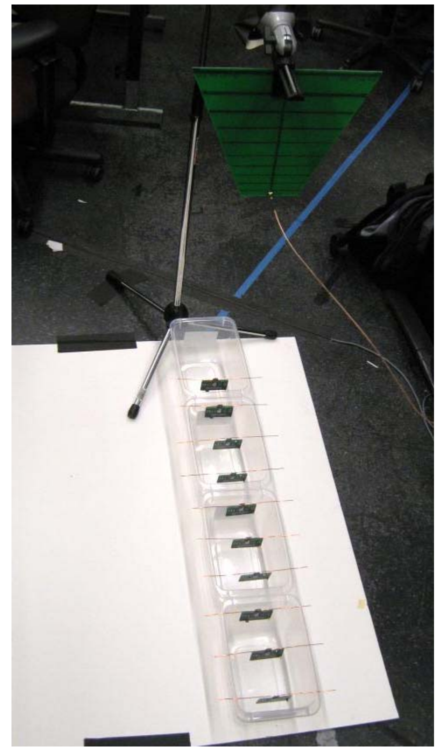
Ambient Backscatter: Wireless Communication out of Thin Air, Vincent Liu, Aaron Parks, Vamsi Talla, Shyam Gollakota, David Wetherall, Joshua R. Smith, To appear, SIGCOMM 2013

ABC: Ambient Backscatter Communication





Outdoor --- Fully ambient!
100 bps achieved



Indoor test app
Tags able to detect improper order within 30s of applying the RF source

Ambient Backscatter: Wireless Communication out of Thin Air, Vincent Liu, Aaron Parks, Vamsi Talla, Shyam Gollakota, David Wetherall, Joshua R. Smith, To appear, SIGCOMM 2013

Demonstrated RF powered, battery free

Environmental Sensing

Temperature [NEMO]

Input devices

Accelerometer [WISP]

Touch Sensing [Capacitive touch WISP]

EEG [EEG WISP]

` Microphones [Analog Backscatter]

Cryptography

RC5 [WISP], AES [BTAG]

Location systems

cm-precision, non-camera [ULTRASOUND WISP]

Displays

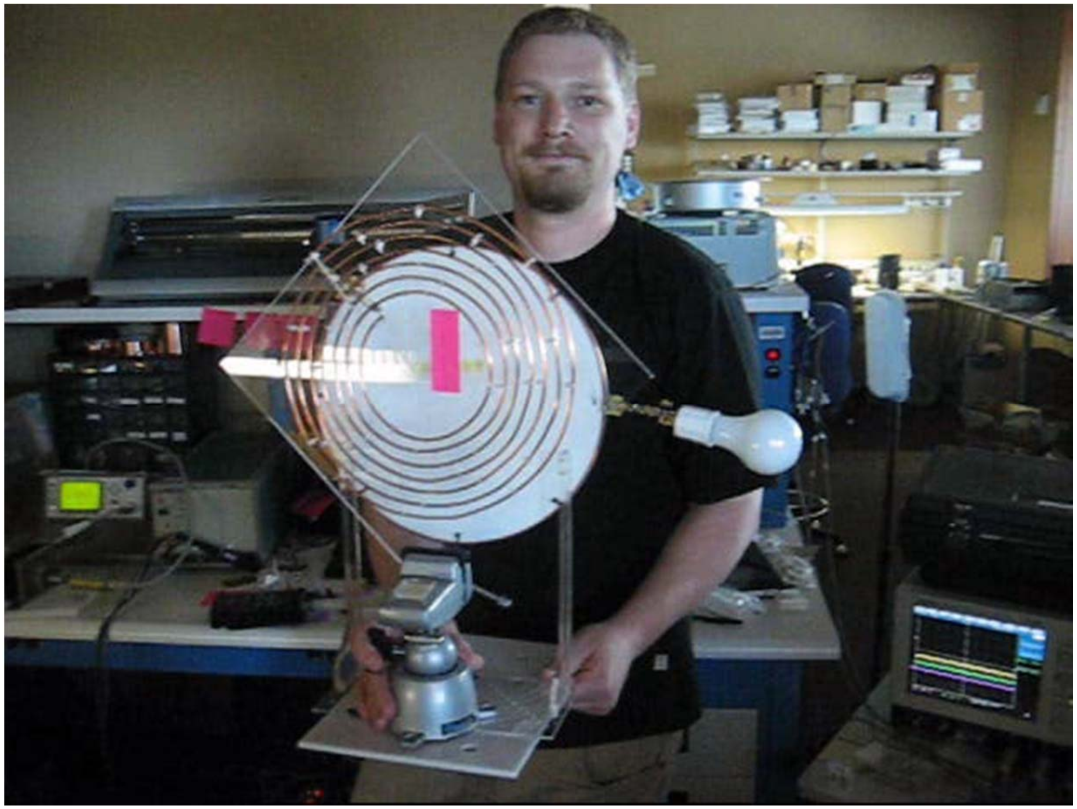
NFC-WISP E-Ink display

Peer to peer communication

“Readerless RFID” [ABC]

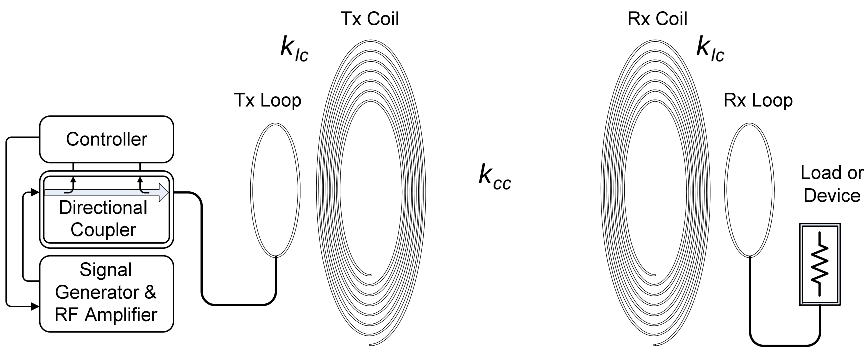
WREL: Wireless Resonant Energy Link

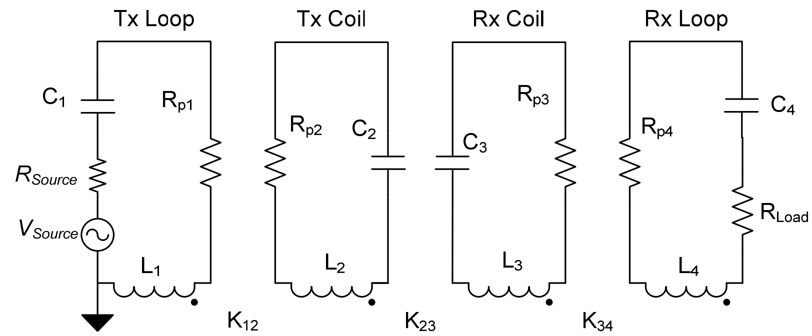
WREL: Wireless Resonant Energy Link



60W transferred ~3 feet, +75% efficiency

WREL System



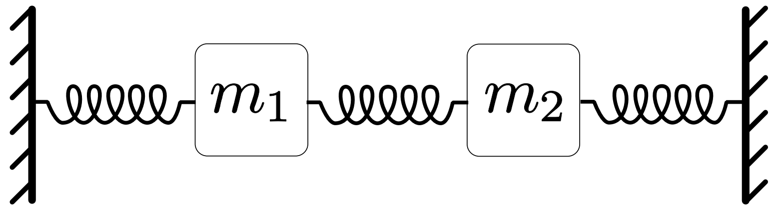


$$V_{Gain} \equiv \frac{V_{Load}}{V_{Source}} = \frac{i\omega^3 k_{12} k_{23} k_{34} L_2 L_3 \sqrt{L_1 L_4}\, R_{Load}}{k_{12}^2 k_{34}^2 L_1 L_2 L_3 L_4 \omega^4 + Z_1 Z_2 Z_3 Z_4 + \omega^2 \left(k_{12}^2 L_1 L_2 Z_3 Z_4 + k_{23}^2 L_2 L_3 Z_1 Z_4 + k_{34}^2 L_3 L_4 Z_1 Z_2 \right)}$$

where

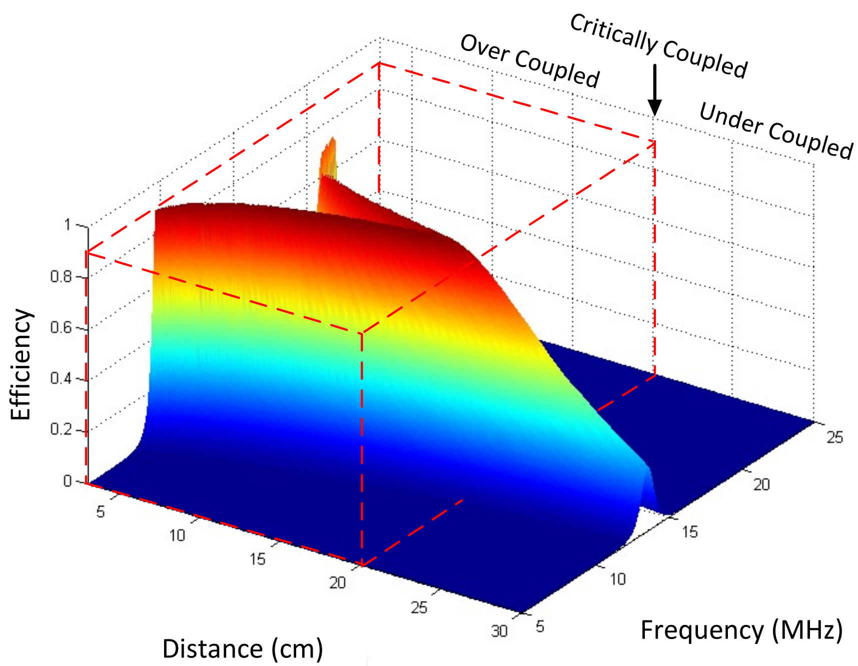
$$\begin{aligned}
Z_1 &= (R_{p1} + R_{Source} + i\omega L_1 - i/(\omega C_1)) \\
Z_2 &= (R_{p2} + i\omega L_2 - i/(\omega C_2)) \\
Z_3 &= (R_{p3} + i\omega L_3 - i/(\omega C_3)) \\
Z_4 &= (R_{p4} + R_{Load} + i\omega L_4 - i/(\omega C_4))
\end{aligned}$$

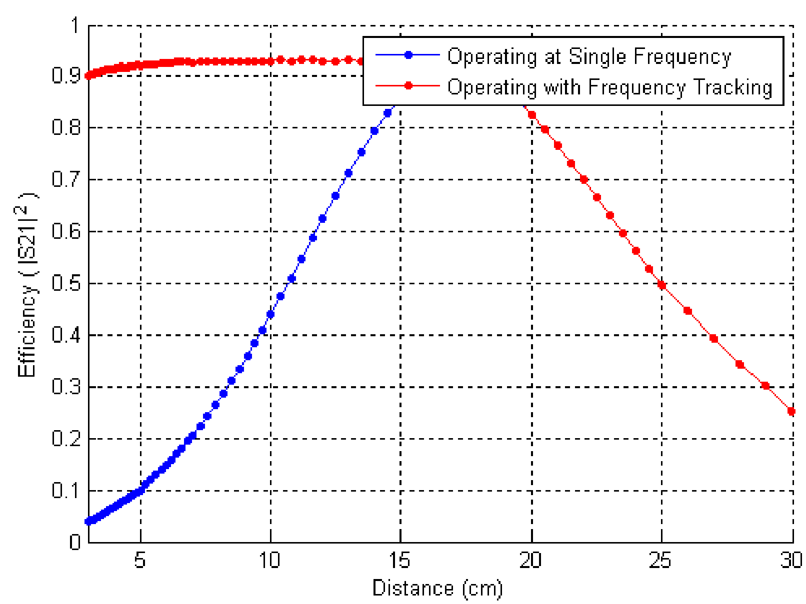
Coupled resonators



Auto-Tuning

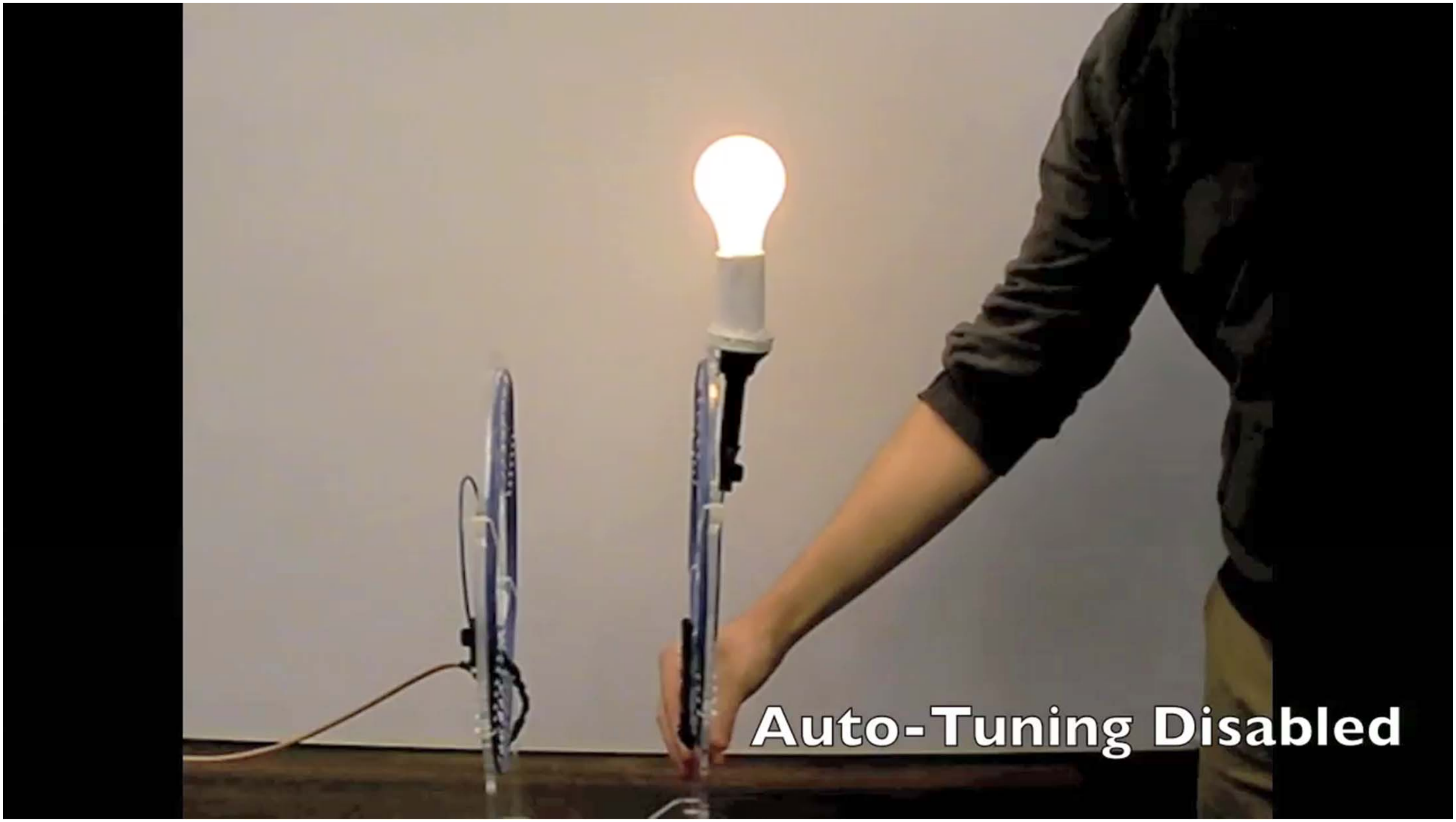
- **Concept**: Dynamically tune system for maximum efficiency
- **Limitations**: Government regulations, complex control algorithms
- **Methods**: Frequency tuning, adaptive impedance matching



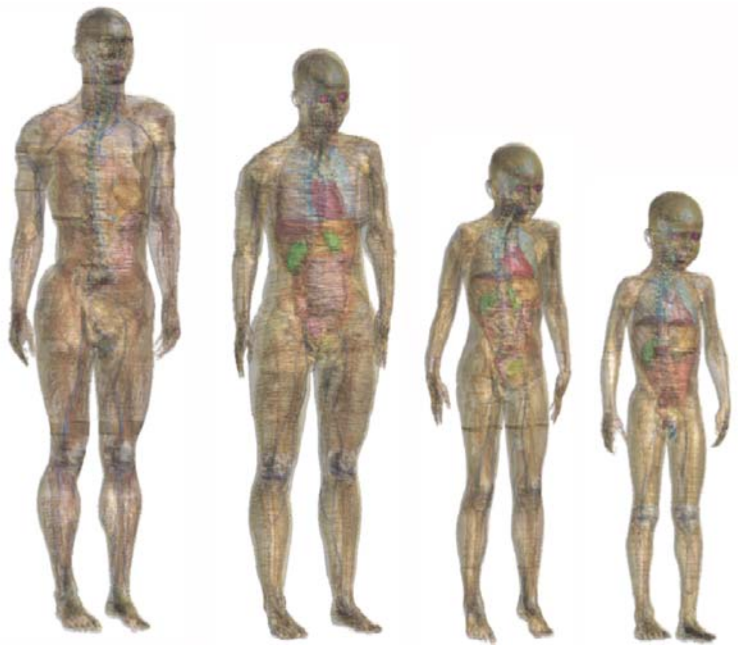


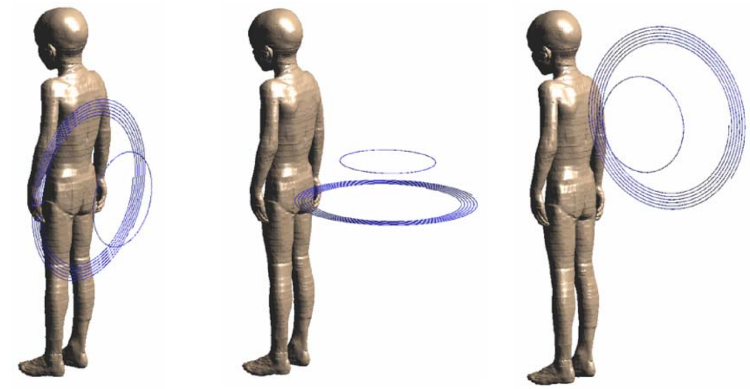
Analysis, Experimental Results, and Range Adaptation of Magnetically Coupled Resonators for Wireless Power Transfer, A.P. Sample, D.T. Meyer, J.R. Smith, *IEEE Transactions on Industrial Electronics, Feb 2011, vol.58, no.2*

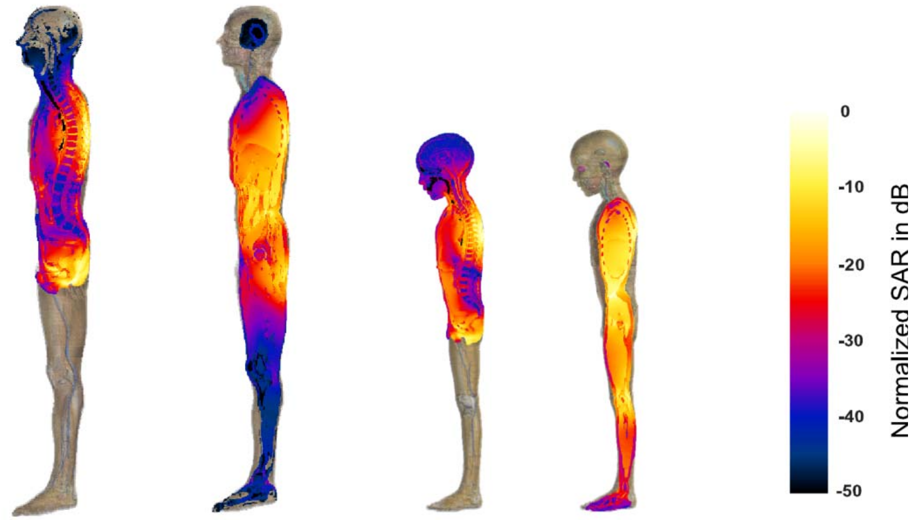
Range and orientation adaptation



RF Health and Science







Evaluation of Wireless Resonant Power Transfer Systems with Human Electromagnetic Exposure Limits, A. Christ, M. Douglas, J. Roman, E.B. Cooper, A.P. Sample, J.R. Smith, N. Kuster. IEEE Trans. Electromagnetic Compatibility, vol. pp, no. 99, pp. 1-10, Oct. 2012.

Applications of WREL

Wireless USB Charging

Hardware

RF power in to resonator on PCB

DC power out USB connector

Single cell Li-Ion charging

Out-of-band (OOB) radio link

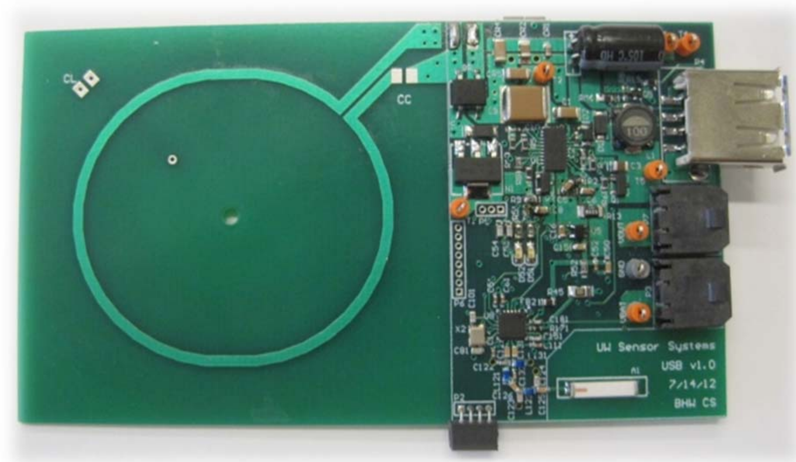
Applications

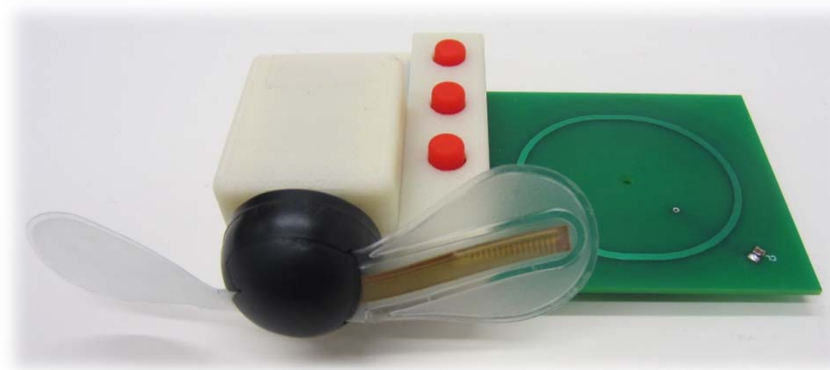
Consumer electronics

- Cell phone
- Wireless SSD

Customizable coil design

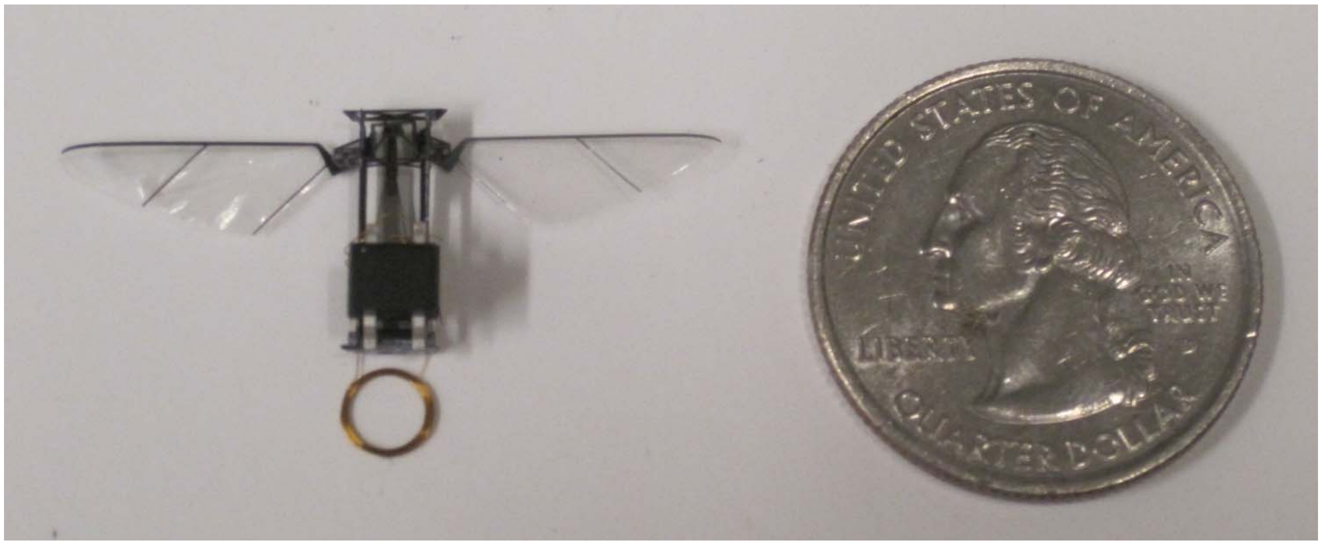
Low-cost evaluation kit





Wireless USB Charging LED Message Fan

Wireless power for Harvard Robobees



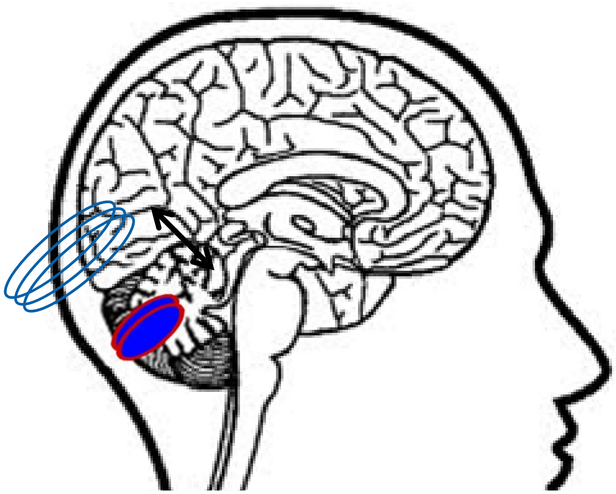
HARVARD
MICROROBOTICS
LABORATORY

Rob Wood et al.

Driving high voltage piezoelectric actuators in microrobotic applications, M. Karpelson, G.-Y. Wei, and R.J. Wood, J. Sensors and Actuators A: Physical, 2011.

Monolithic fabrication of millimeter-scale machines, P. Sreetharan, J. P. Whitney, M. Strauss, and R. J. Wood, J. Micromech. Microeng., vol. 22, no. 055027, 2012.

Fully Implanted ElectroCorticography (ECoG)



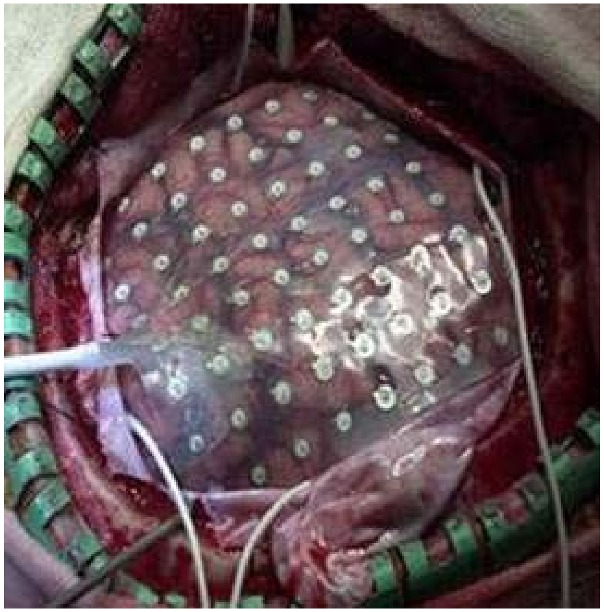
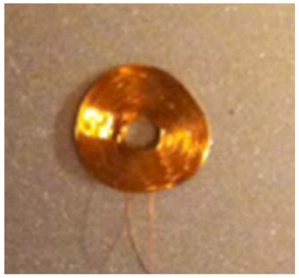
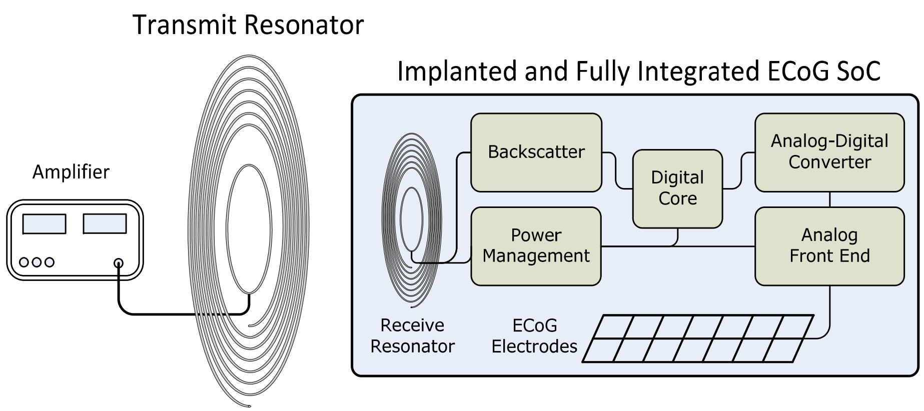
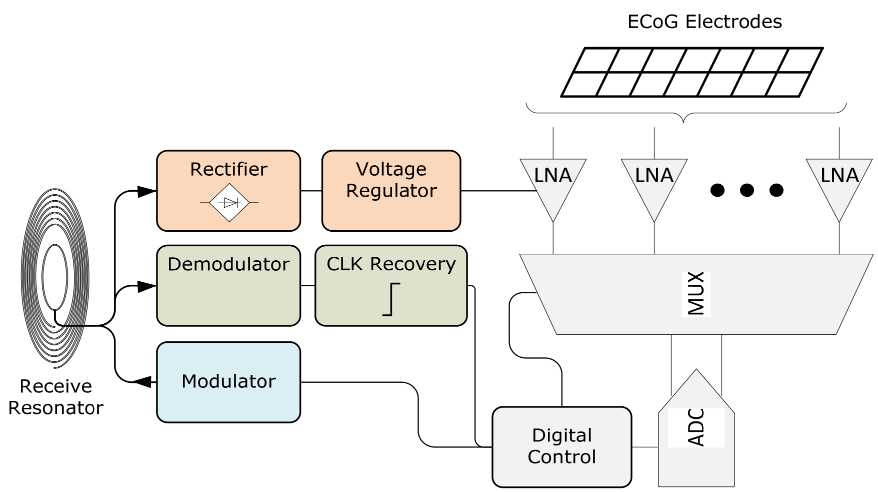


Photo: Gerwin Schalk (Wadsworth Center, Albany, USA) and Kai Miller, Jeff Ojemann (UW).



ECoG IC & System

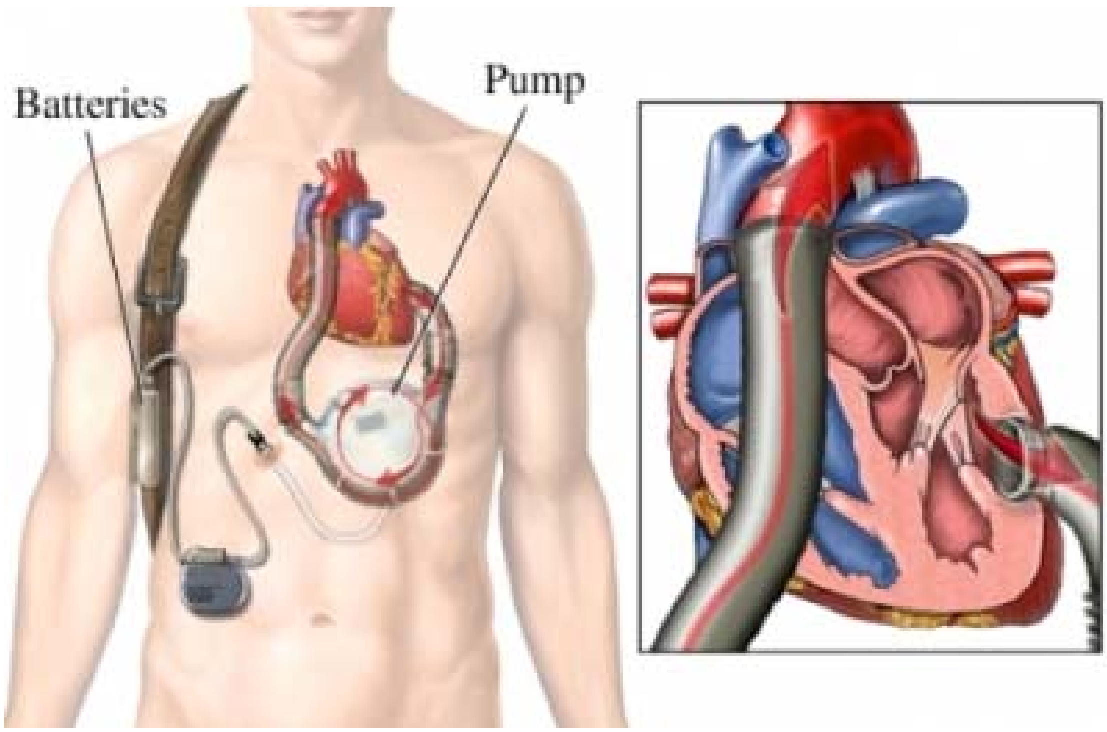




Left ventricular assist device

Yale University
School of Medicine

UNIVERSITY OF WASHINGTON
ELECTRICAL ENGINEERING



Dr. Pramod Bonde, M.D.
Professor of Cardiac Surgery
Dir, Mech. Circulatory Support
Yale School of Medicine

Free-range Resonant Electrical Energy Delivery System (FREE-D)

Yale University School of Medicine

UNIVERSITY OF WASHINGTON ELECTRICAL ENGINEERING

Impact for Heart Failure Treatment

TODAY

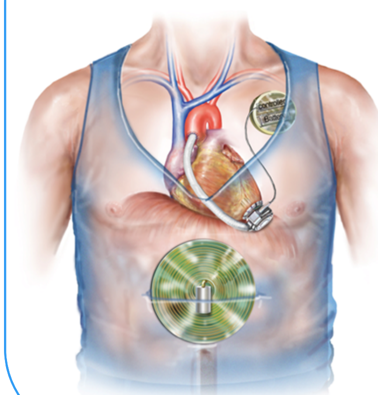
- 35 billion dollar industry
- 30,000 deaths per year
- 2,300 donor hearts available
- NEED: infection free, lifelong LVAD

Wirelessly powered LVADs will become the preferred method of treatment

Problem with LVADs

- Infection
- Driveline
- Repeated Hospitalization
- Surgical Interventions
- Reduced Quality of Life

FREE-D System Solution

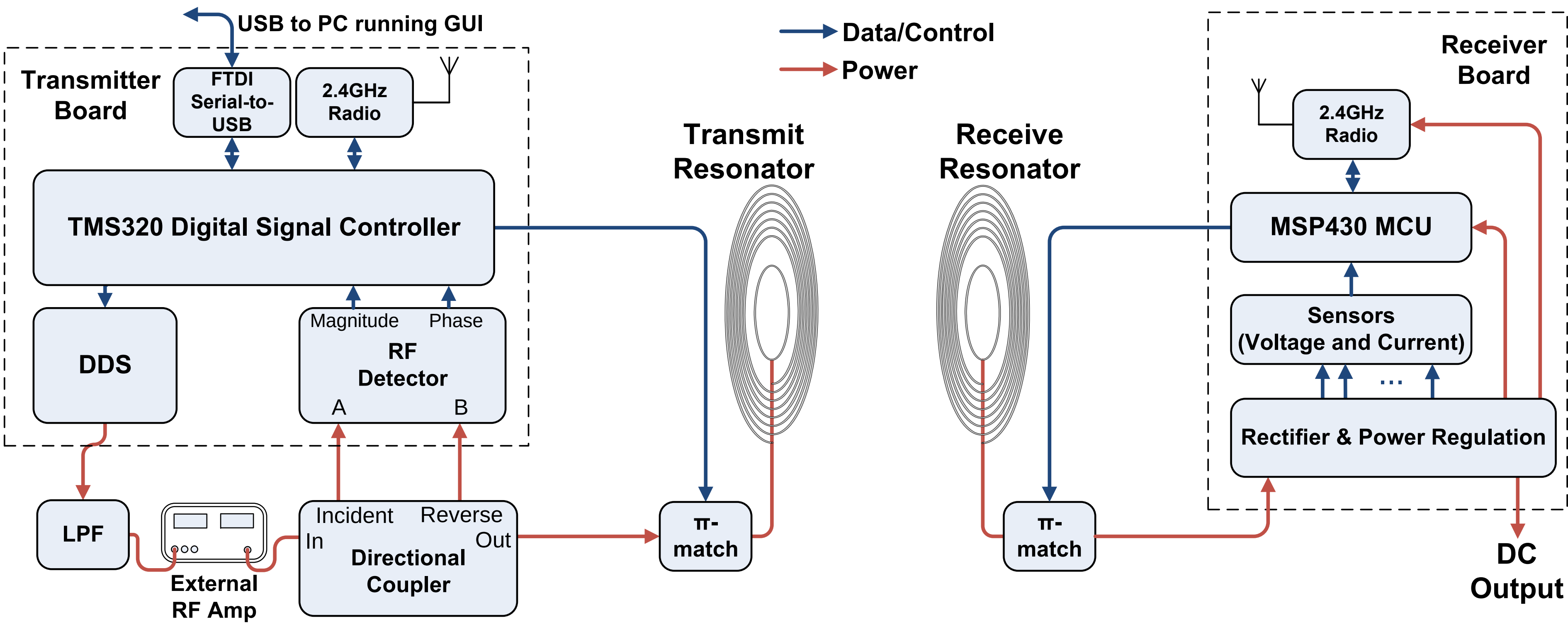


- Free from infection
- Tether-free
- Reduced Hospitalization
- Fully implanted LVAD
- Improved Quality of Life

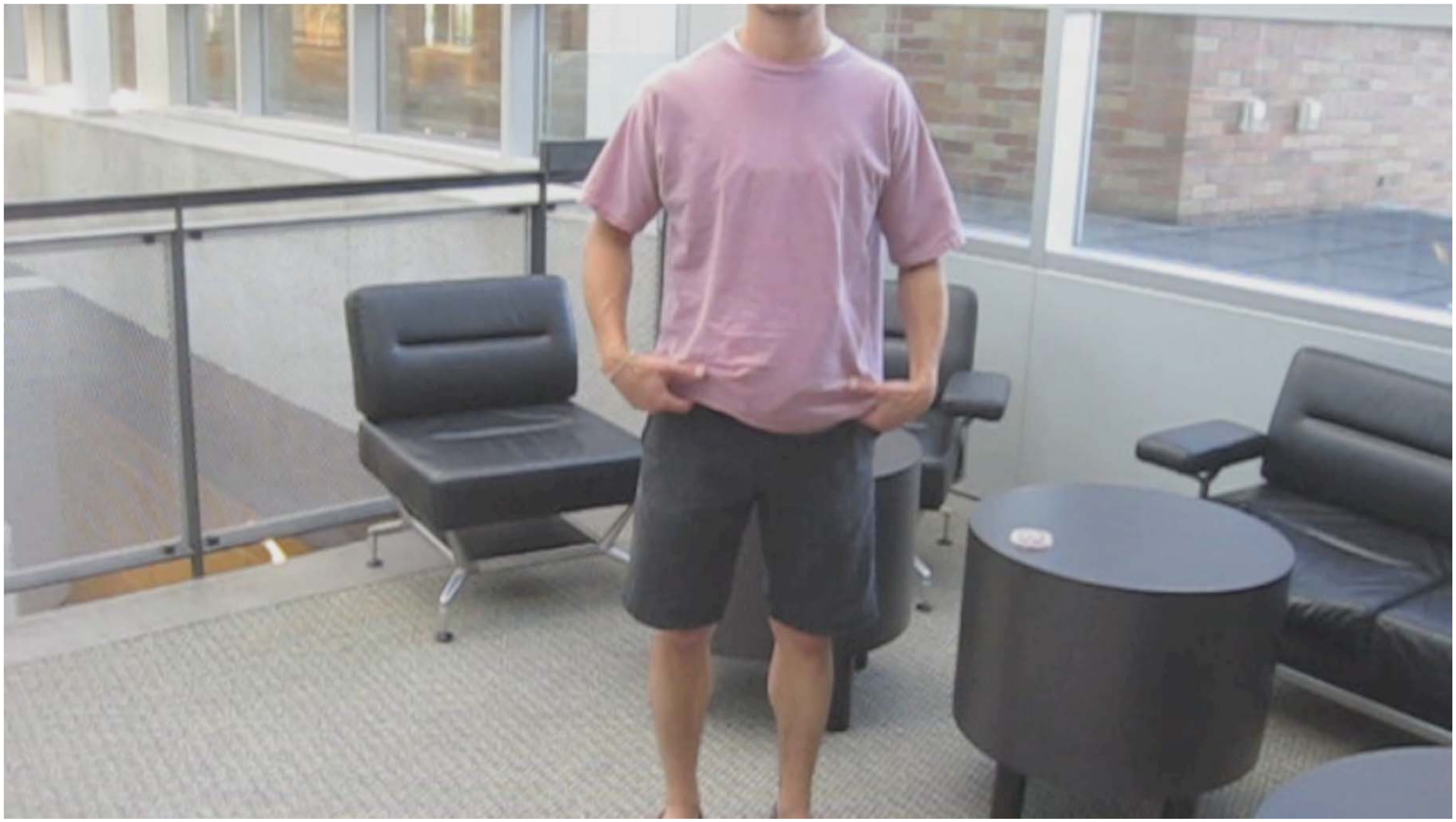
Powering a VAD with the FREED System, B.H. Waters, A.P. Sample, P. Bonde, J.R. Smith, Proceedings of the IEEE, Vol. 100, No.1, pp.138-149, Jan. 2012.

FREED won ***Sezai Innovation Award at 19th ISRB 2011***; FREED won ***Kolff / Olsen Award at ASAIO 2011***

Hardware Block Diagram



FREED Portable TX



A Portable Transmitter for Wirelessly Powering a Ventricular Assist Device Using the FREED System, B.H. Waters, J.T. Reed, K.R. Kagi, A.P. Sample, P. Bonde, and J.R. Smith, in Wirelessly Powered Sensor Networks and Computational RFID, J.R. Smith, Ed., Springer, February 2013.

The space of wirelessly powered systems

	Far field	Near field
Planted	**WISP**	**WREL** **FREED**
Wild	**WARP** **ABC**	**?**

Implications

Zero-power SMS / voice communication?

Increasingly feasible to run mobile/ubiquitous computers using RF power

Perpetual sensors embedded permanently in structures, human bodies

Book!

WISP
power
sensor
RFID
reader
tag
energy
voltage
data
tags
antenna
consumption
signal
input
wake-up
range
UHF
digital
passive
time
sensors
capacitor
supply
output
current
microcontroller
communication
protocol
application
implementation
performance
harvesting
powered
network
radio
board
order
applications
number
state
sensing
results
shows
measurement
information
different
monitor
systems
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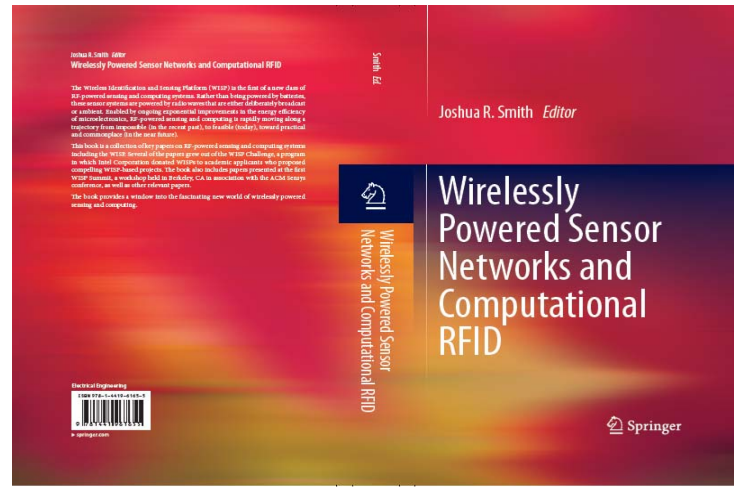
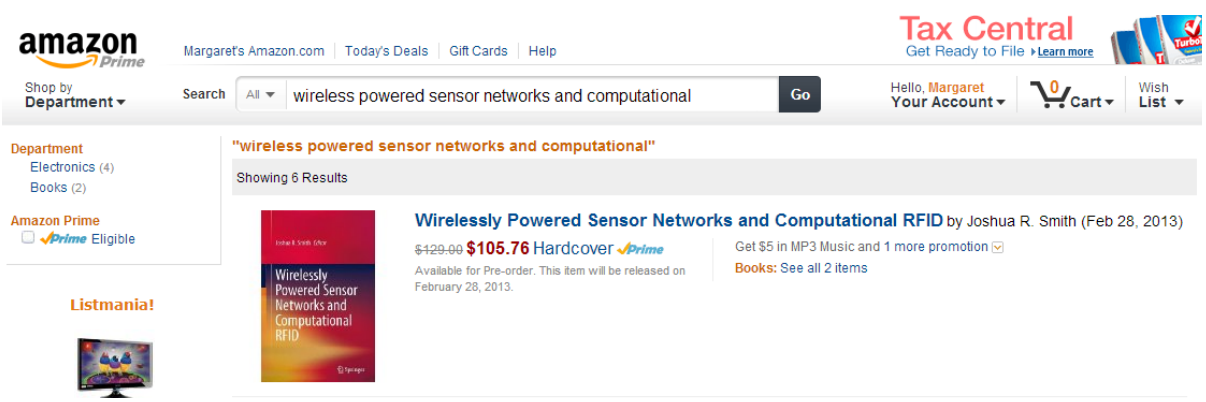
IEEE
EPC
system
transmission
design
available
one
POW
wireless
analog
rate
frequency
higher



Joshua R. Smith Editor
Wirelessly Powered Sensor Networks and Computational RFID
Springer
Wirelessly Powered Sensor Networks and Computational RFID
Smith Ed.



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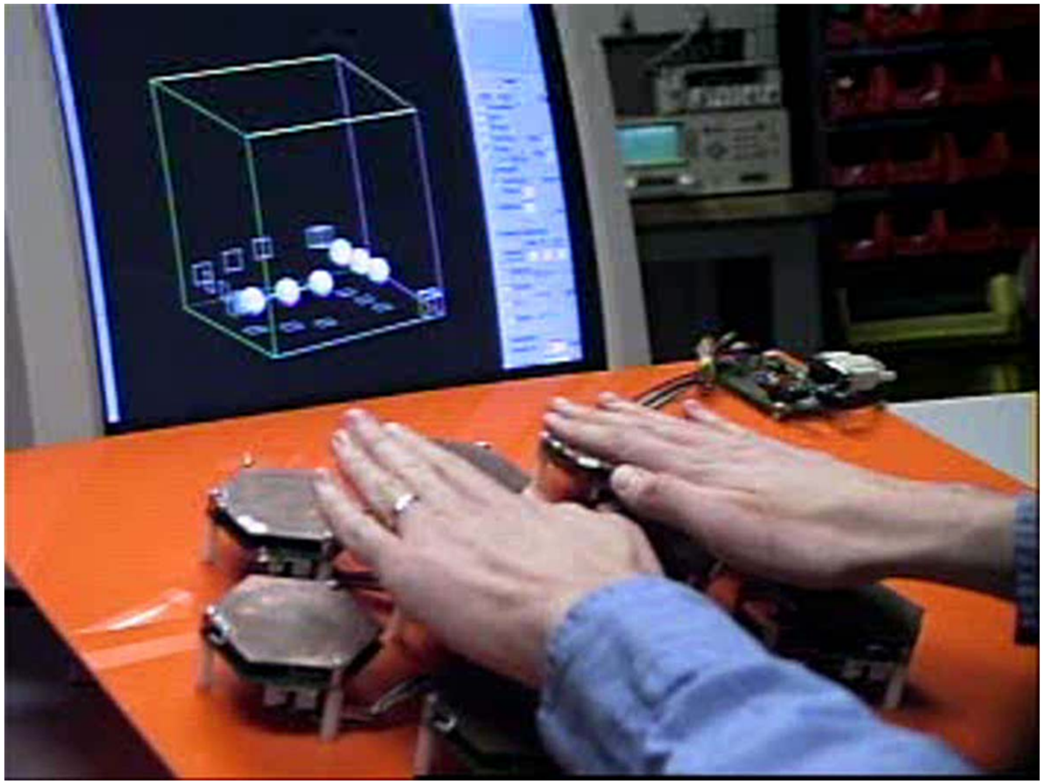
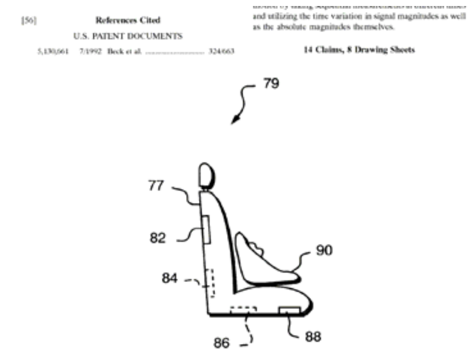
Robotics

Electric Field Sensing

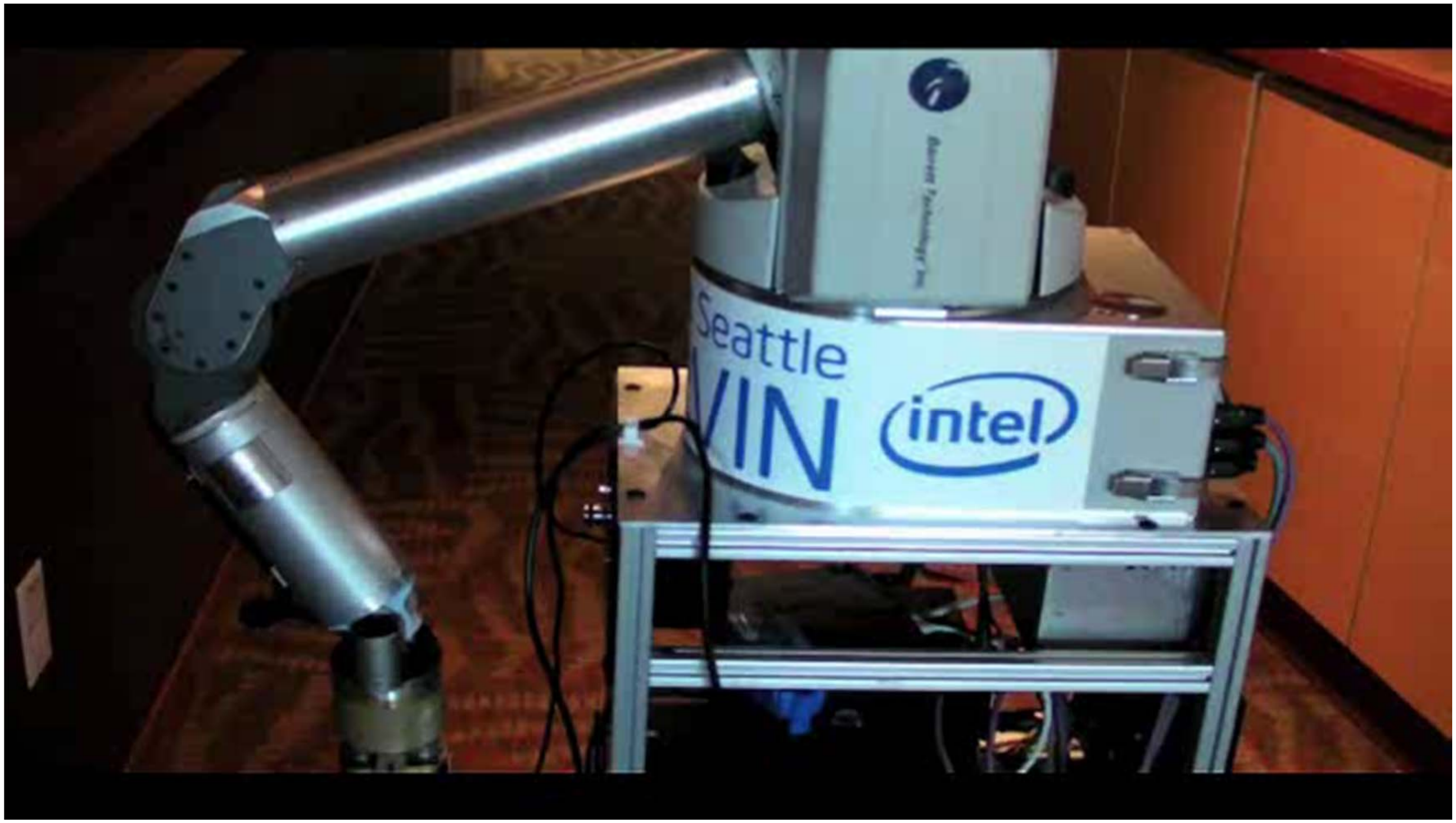
Licensed by Honda and now standard in all Honda cars.



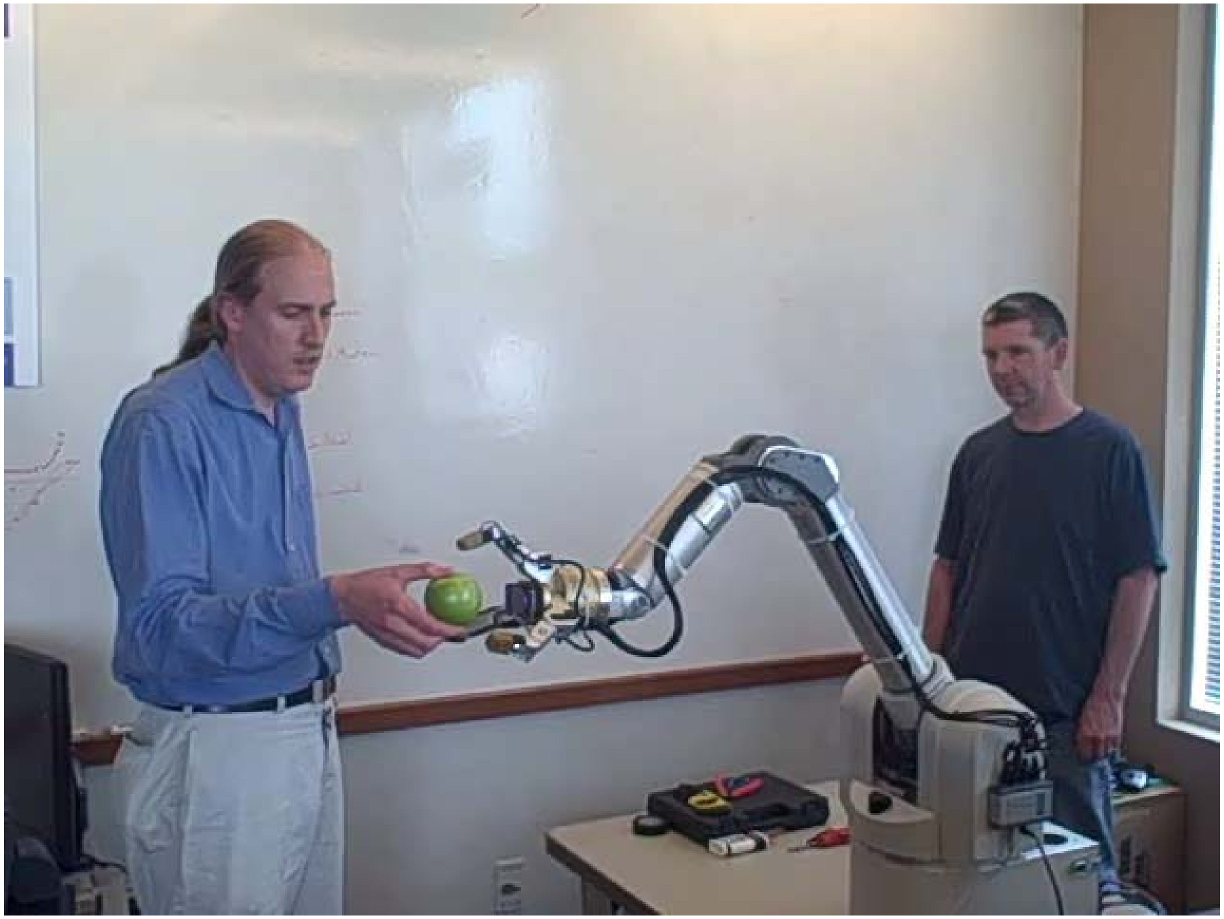


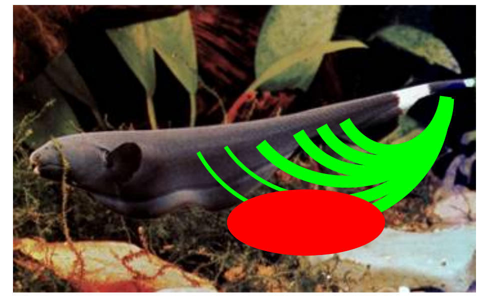
Field Mice: Extracting Hand Geometry From Electric Field Measurements, Joshua R. Smith. IBM Sys. J, Vol. 35, No. 3&4, 1996, pp 587-608.

Marvin finds its food by “smelling” electric fields!



Electric Field Pretouch



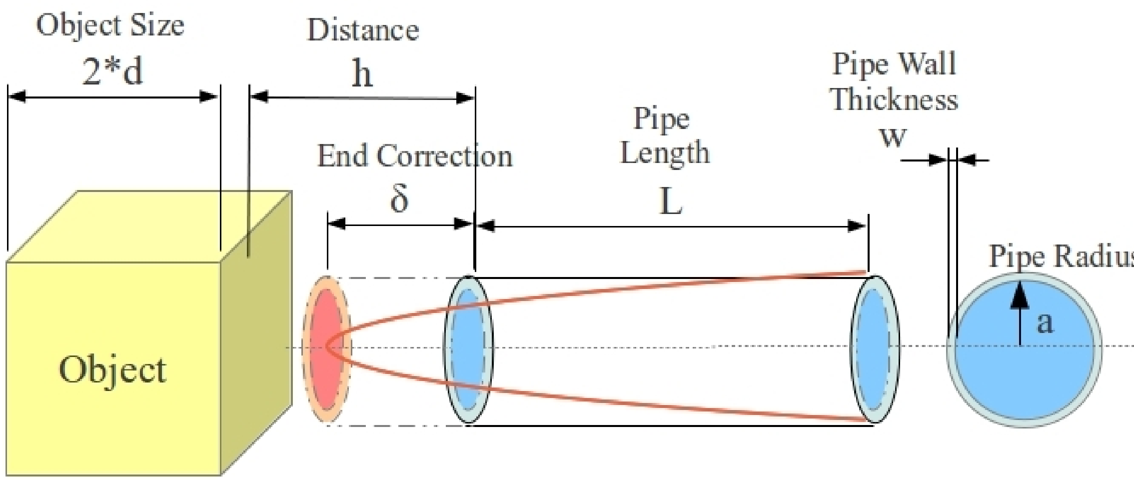


Black ghost knife fish (*Apteronotus albifrons*) uses "electrosense"

An Electric Field Pretouch System for Grasping and Co-Manipulation, Brian Mayton, Louis LeGrand, Joshua R. Smith. Proceedings of ICRA, May 2010.

Seashell Effect

- **“Hearing the sea”** from seashell
- **Pitch** changes with the distance
- **Environmental noise** amplified most at the cavity’s resonant frequency, which changes as the cavity approaches an object



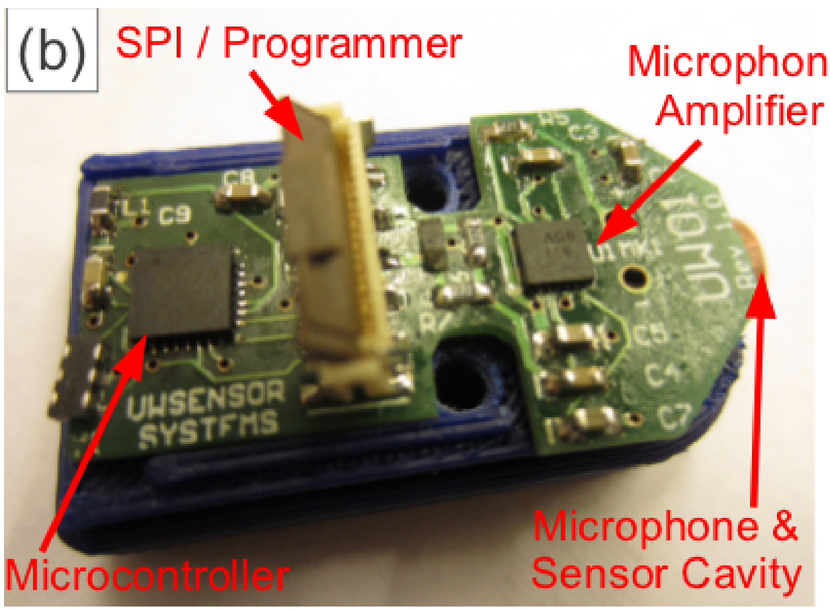
End correction: $$\delta_{obj} = \frac{a}{3.5(h/a)^{0.8}(h/a+3w/a)^{-0.4}+30(h/d)^{2.6}}$$

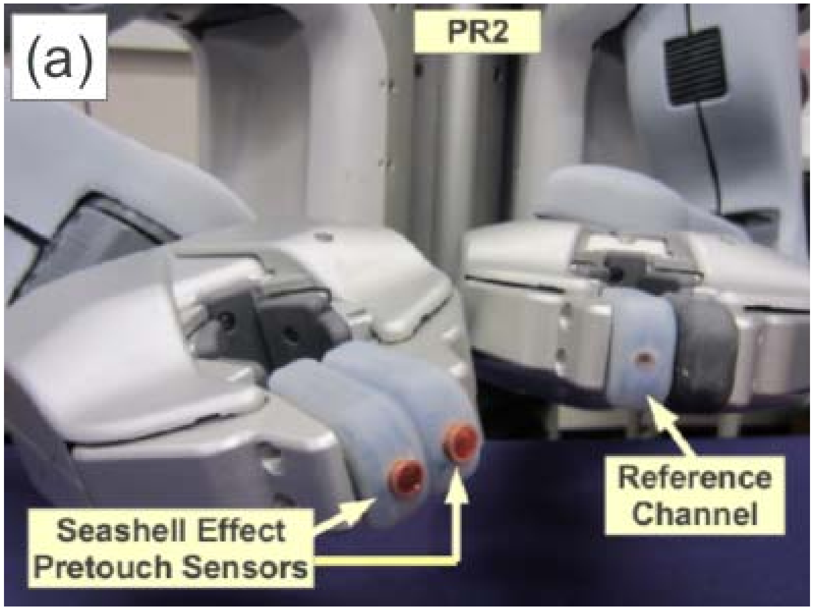
Shorter distance → Longer Effective Pipe Length → Lower Resonance Frequency

Idea: Develop a pretouch sensor using the seashell effect

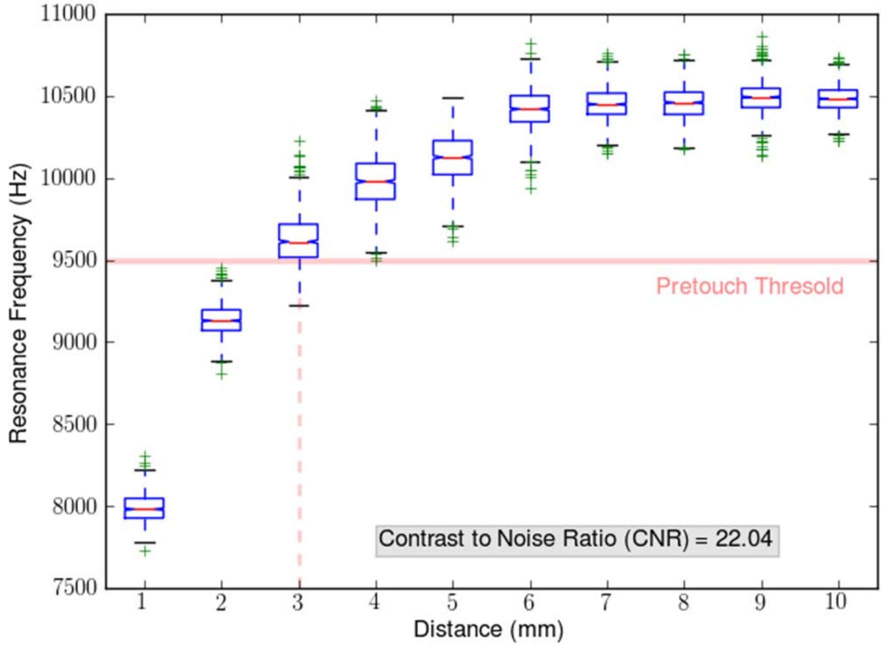
Sensor Hardware

- Microphone + Cavity
- Resonant frequency estimation
- Footprint: 10mm x 5mm
- 8-bits microcontroller
- Fully integrated to Willow Garage's PR2's gripper

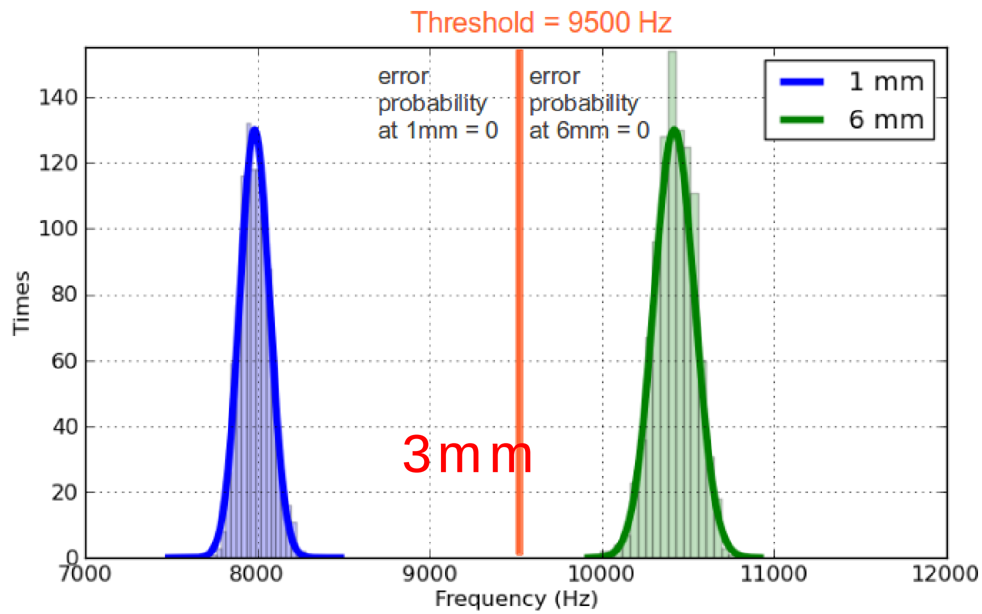




Sensor Performance



1000 sensor readings at each of 1~10 mm



1 mm & 6 mm comparison

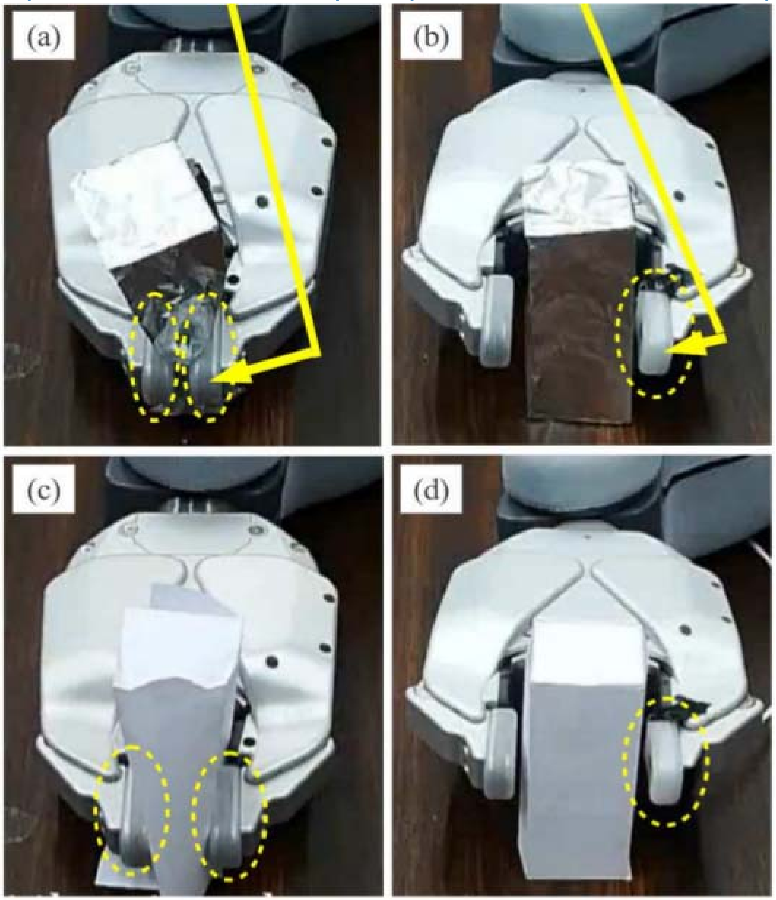
- Select Threshold for Binary Detection:

Frequency: 9500 Hz @ 3mm

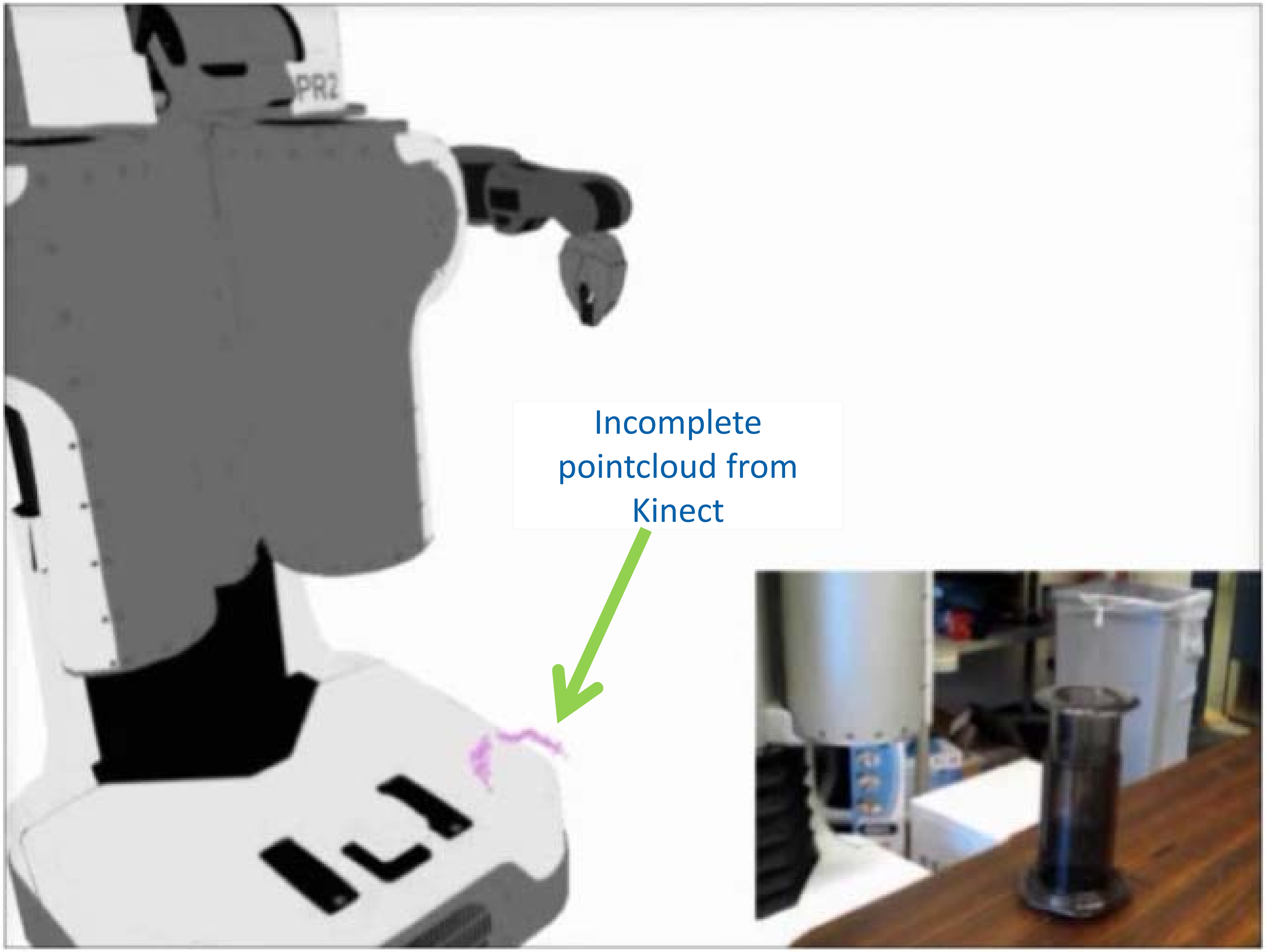
Application I: Reactive Grasping

- ❑ Detect highly compliant and insubstantial object

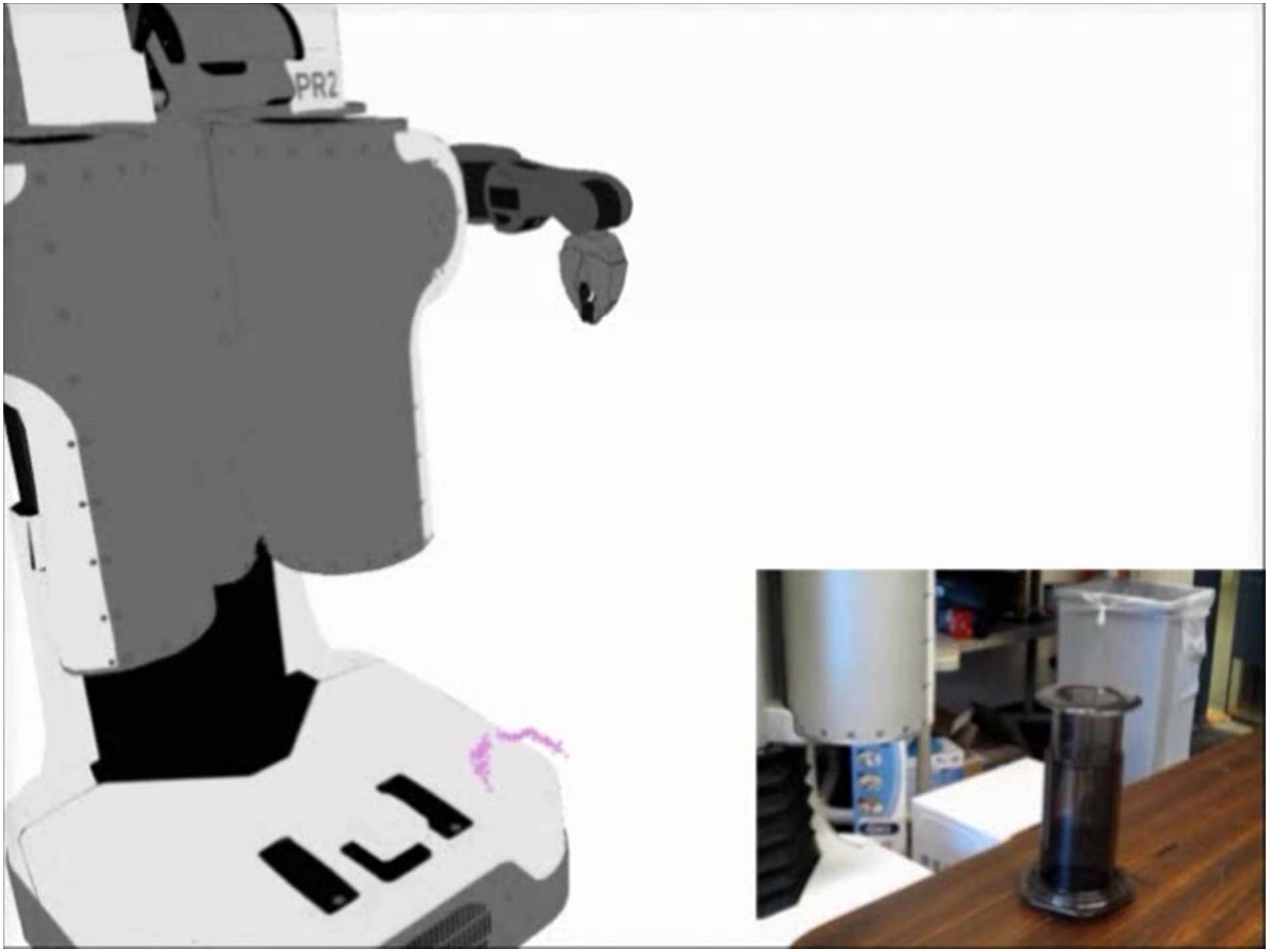
Pressure Sensor (threshold: 0.05 N) | Seashell Pretouch (threshold: 9500 kHz)



Video

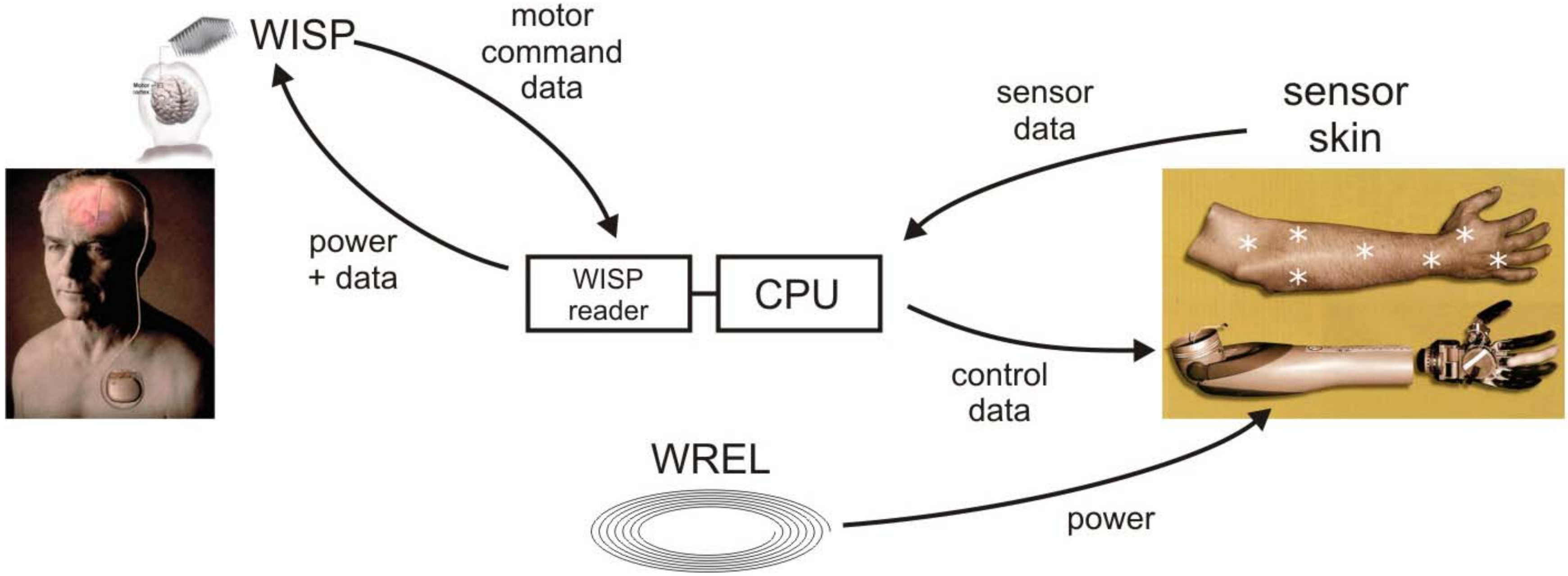


Video



CeBIT 2009 Kickoff

Putting it all together



More information:

http://sensor.cs.washington.edu

jrs@cs.washington.edu