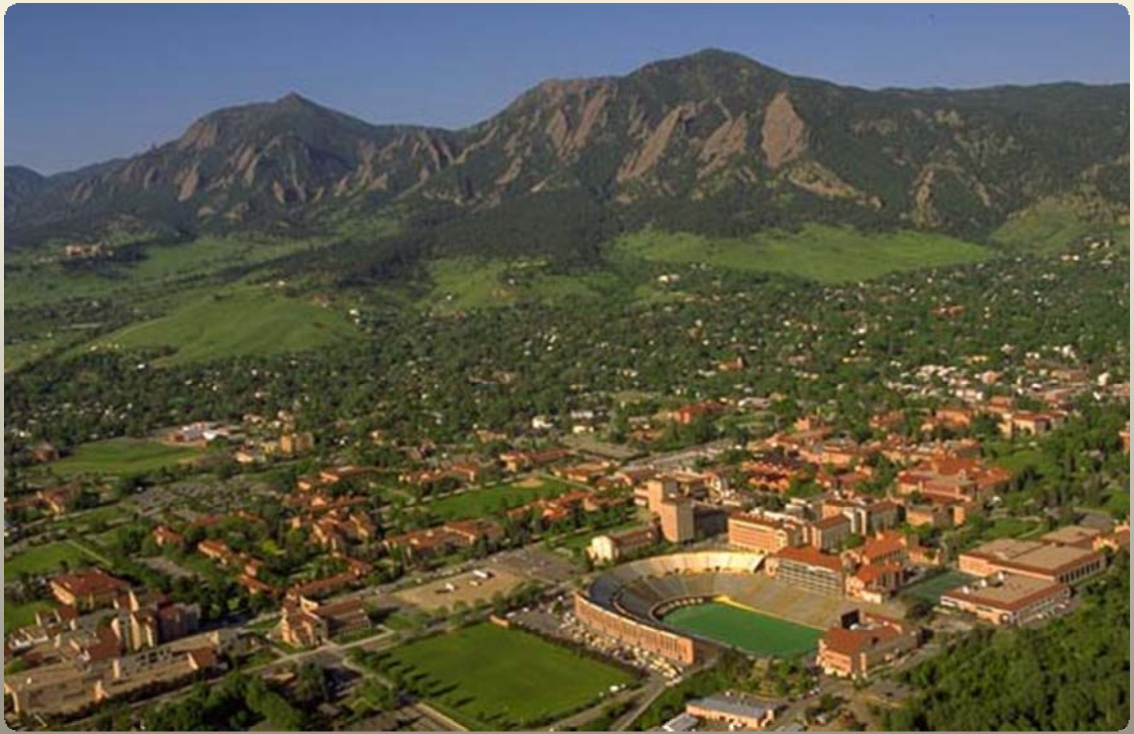
Batteryless MicroPower Sensors for Context Aware Technologies

Faculty: Zoya Popovic and Regan Zane

Students: C. Davis, A. Dolgov, E. Falkenstein, J. Morroni, T. Paing, J. Shin



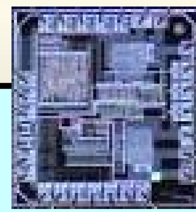
Colorado Power Electronics Center and Microwave Active Antenna Group
Department of Electrical and Computer Engineering
University of Colorado at Boulder

Wireless Power for Miniature Sensors

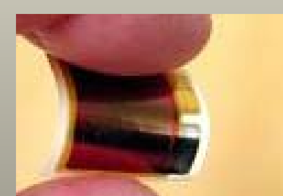
Goal: *<u>Eliminate</u> wires and battery replacement from sensor applications*

Approach: Efficiently <u>harvest energy</u> from RF sources through integrated design of rectifying antenna (rectenna) elements and energy harvesting circuitry. Both are optimized for operation at ultra low power levels.

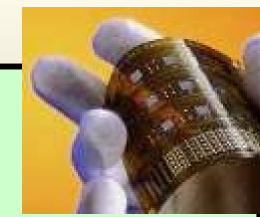
RF Rectenna Designs



Peak-Power Tracking Energy Harvester



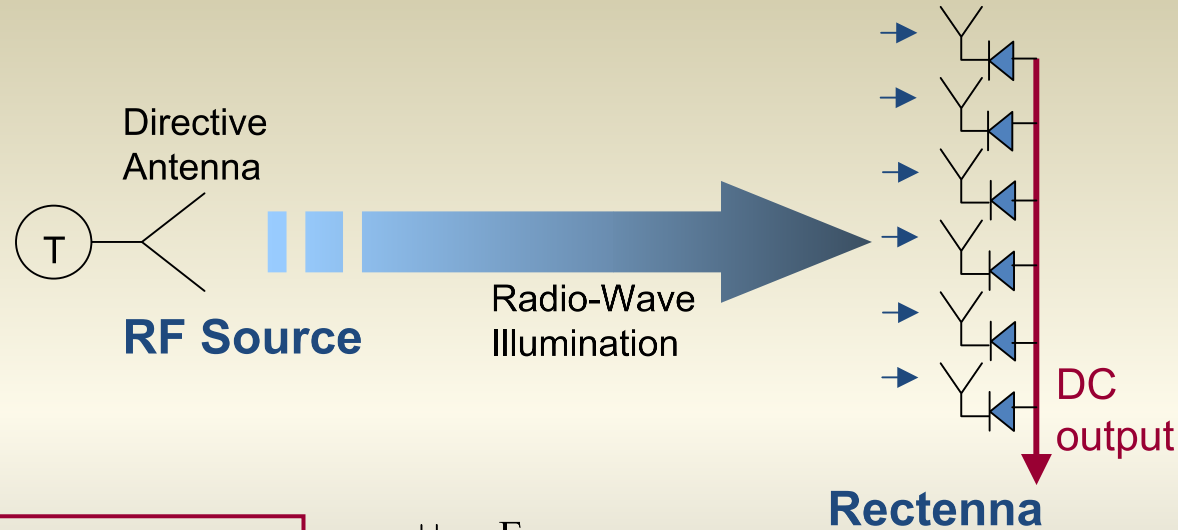
Energy Storage (Thin Flexible)



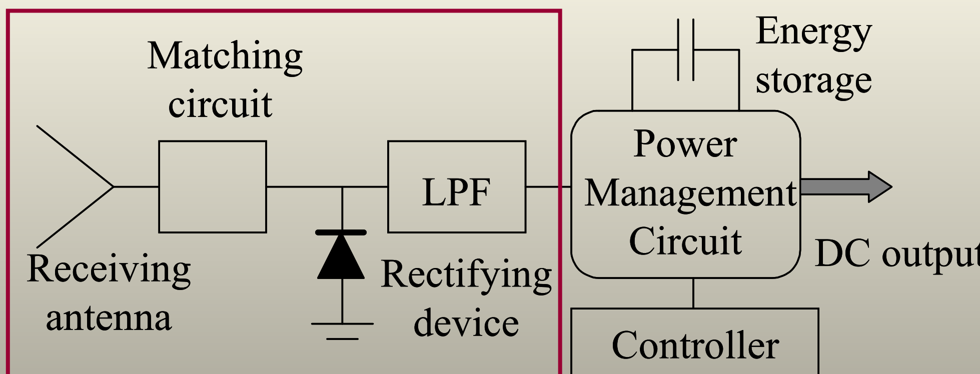
Low-Power Wireless Sensor

RF -Wireless Power Source

Since the 1950s:
- ***inductive coupling***
(not really waves)
- ***RFID***
(near field, low power)
- ***high-power beaming***
(SSPA)



Polarization
Harmonics
Efficiency



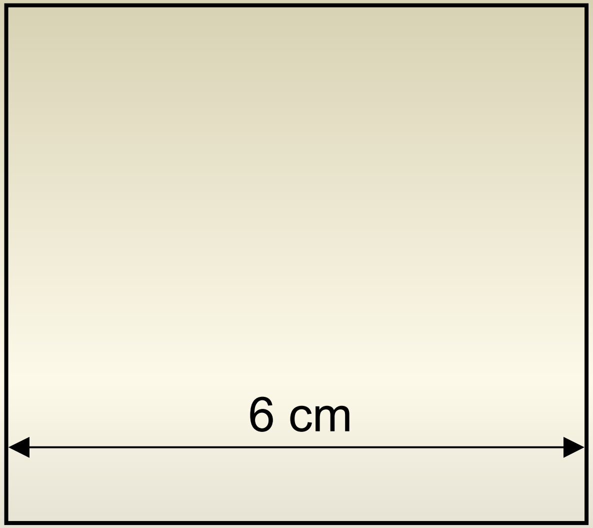
Powers some application
e.g. a low-power sensor

Nicola Tesla's patent No. 685,954, Nov.5, 1901, Claim 11:
"…utilizing effects or disturbances transmitted through the natural media from a distant source, which consists in storing in a condenser … electrical energy derived from an independent source, and using, for periods of time predetermined as to succession and duration, the accumulated energy so obtained to operate a receiving device."

Rectenna Design Considerations

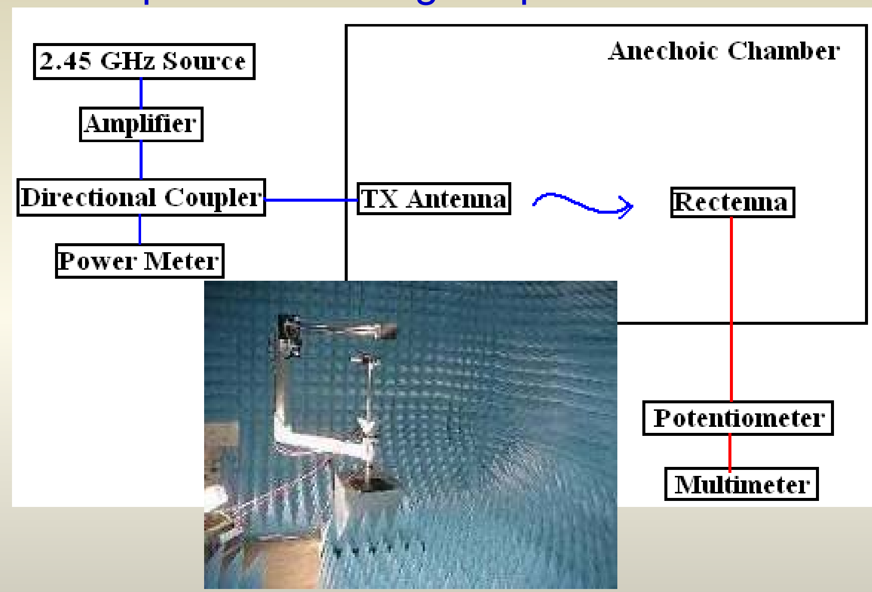
- **Incident wave frequency and power density** – given by transmitter, can be narrowband, multiband or wideband. Power varies depending on application from mW to μW/cm²
- **Incident wave polarization** – the antenna can be polarized linearly, circularly or non-polarized (elliptical). In a multipath environment, polarization is likely to vary over the spherical angle - design a dual-orthogonally polarized rectenna to provide less variation in DC power
- **Load impedance** that is required – this will depend on what device will be using the rectified power. We test the rectenna array output as a function of DC load
- **Substrate and metallization** – if a flexible thin substrate is desired, ground-backed antennas such as patches are not likely candidates, spirals and dipoles can be used. If substrate can be thinner, for narrowband sources, grounded patches are best.
- **Antenna array size** – depends on application. Area should be measured in square wavelengths (λ^2). Packing density of antennas in array determines efficiency.
- **Rectification device** – the choice of diode depends on frequency and expected power density levels. Diodes that work well for low power levels will not be best for a higher power case.

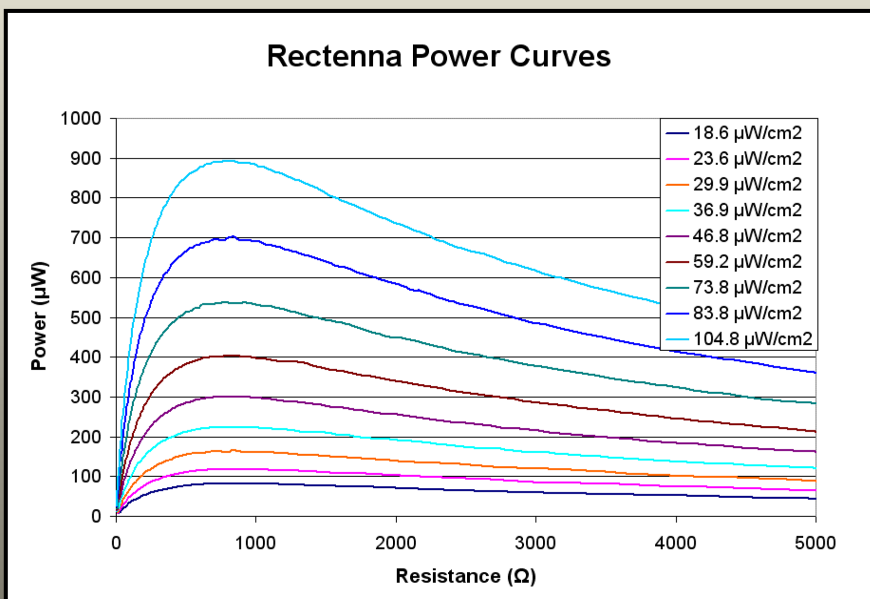
2.45 GHz Rectenna, Dual-Linear Polarization



6 cm x 6 cm Patch Rectenna

Experimental Setup for Measuring Output Characteristics

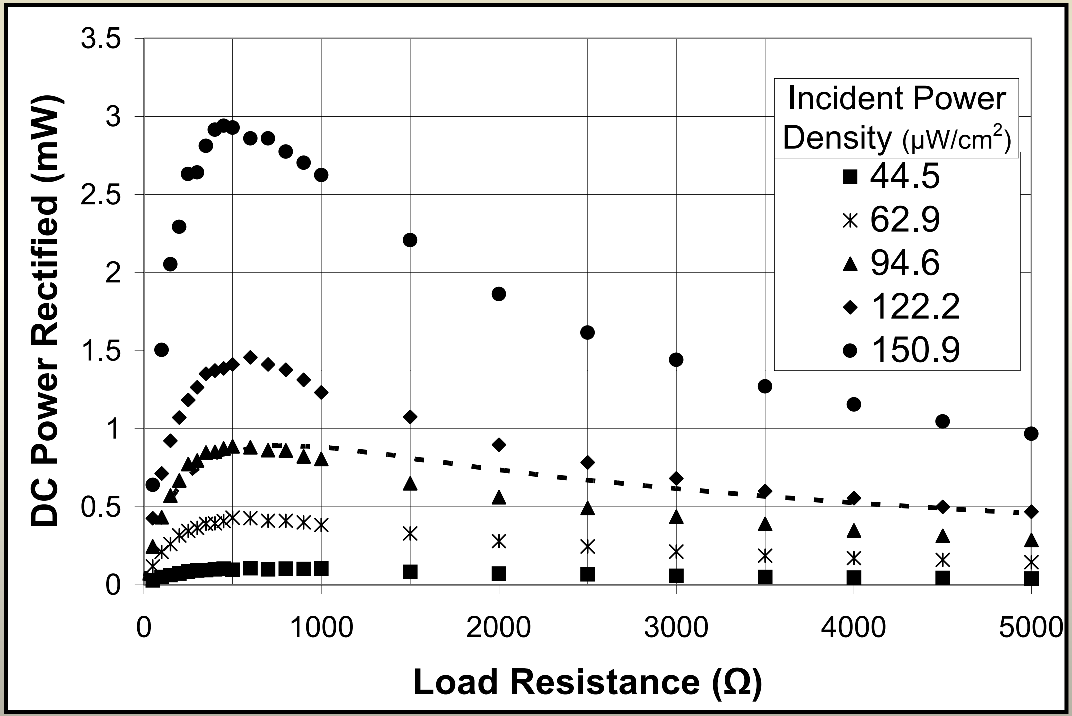




- Dual linear polarization results in near constant output power over full range of 360º rotation
- Over a 10:1 range of input power densities, **optimal load resistance for maximum output power is nearly constant**

Six 4-element Linear Rectenna Arrays

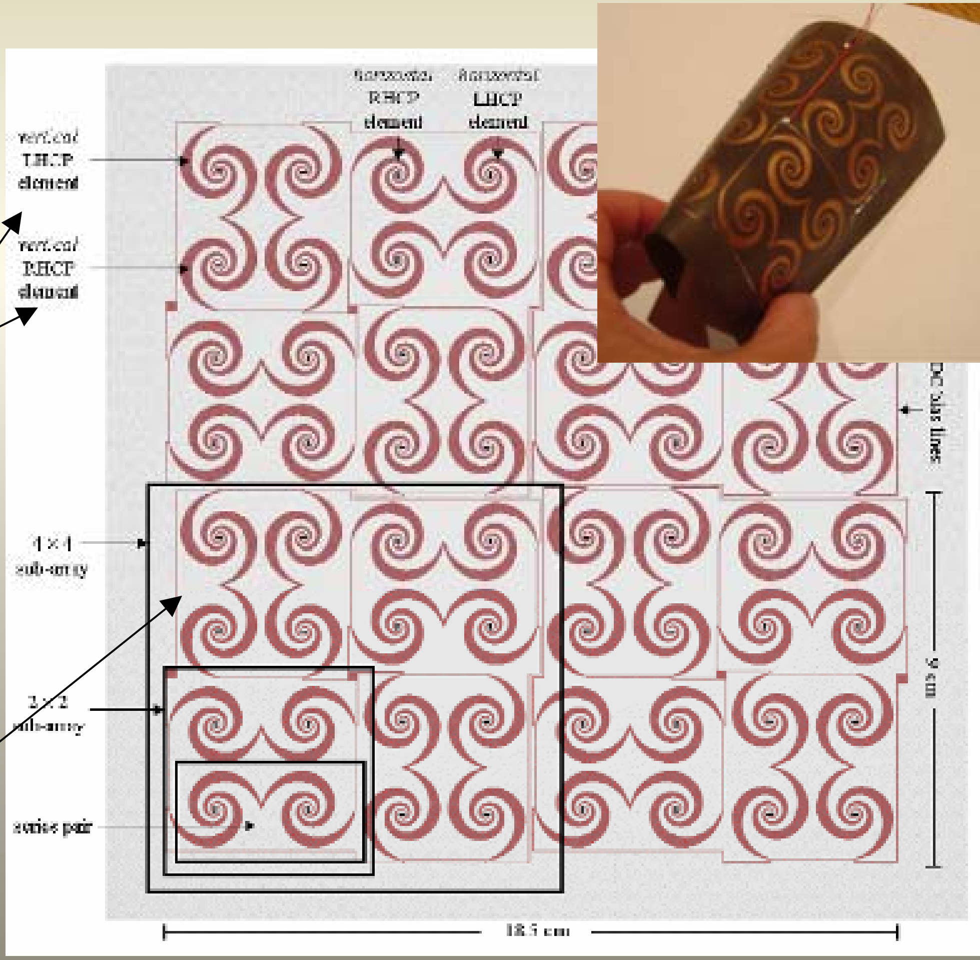
Output characteristics of a single 4-element section



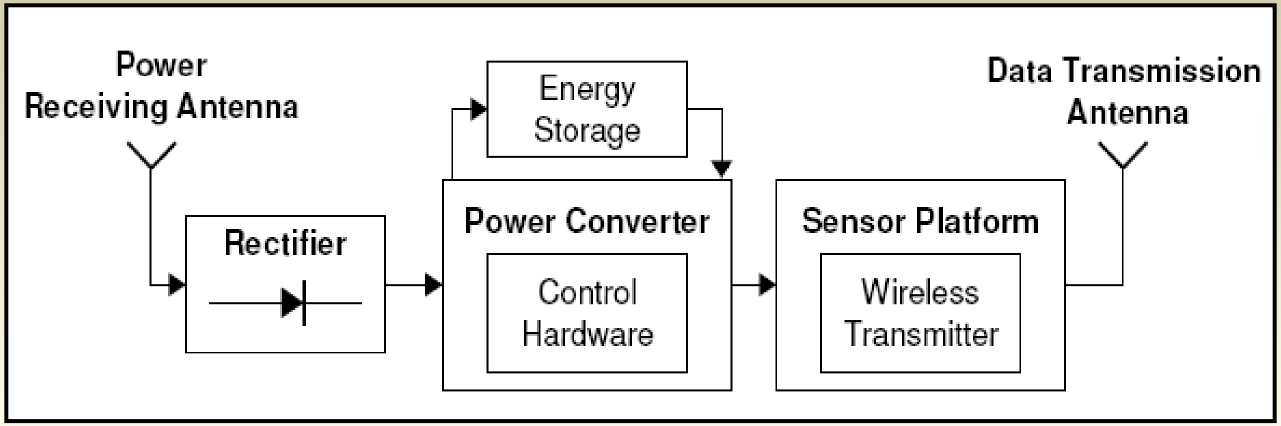
- Can be arranged in a quasi-conformal shape to fit cylinder
- The array has omni-directional pattern (less than 3dB variation)
- It can be mounted on either conductive or dielectric post
- DC of subarrays can be combined in series or parallel
- Again, **nearly constant optimal load resistance**

Broadband Rectenna Array

- For unknown electromagnetic environments, ultra broadband arrays are desirable (2 to 18 GHz)
- Right and left hand circularly polarized spirals give polarization diversity which equalizes DC power in a multi-path environment
- No matching circuit between antenna and diode improves fill factor
- DC output is reconfigurable via series and parallel combinations

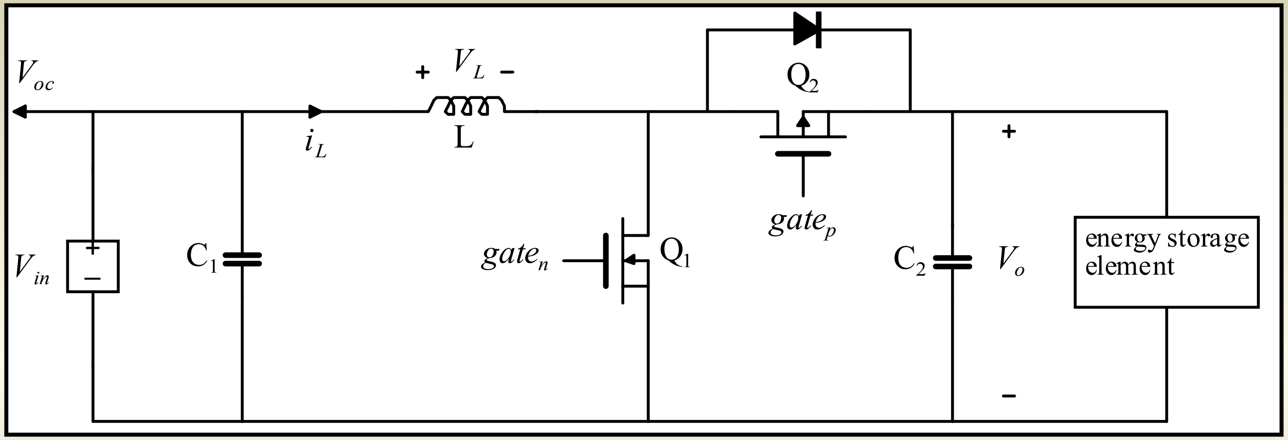


Power Management



- Power converter transfers energy from rectenna to energy storage and delivers DC output
  - Open loop resistor emulation achievable with ultra low power control overhead, **naturally tracks rectenna peak power point** over wide range
    - Converter operated in burst mode with a selectable burst duty cycle
    - During burst operation, converter operates in constant on-time fixed frequency discontinuous conduction mode or variable frequency critical conduction mode
- System efficiency optimization
  - Slow sampling at converter input indicates relative input power level
  - Set parameters for converter emulated resistance and rectenna series / parallel configuration

Boost Converter Analysis



- Resistance emulated of boost converter in DCM dependent on V_{in} and V_o:

$$R_{em\_bst\_dcm} = \frac{2 \cdot L \cdot T_{hf}}{t_1^2 \cdot k}\left(\frac{M-1}{M}\right) \quad \text{for} \quad V_{in} << V_o \Rightarrow R_{em\_bst\_dcm} = \frac{2 \cdot L \cdot T_{hf}}{t_1^2 \cdot k}$$

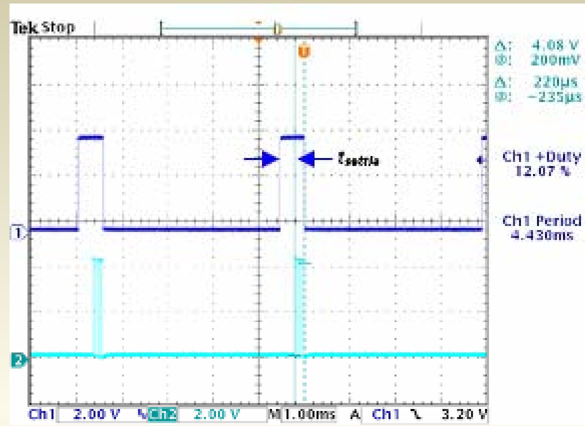
- Boost converter in CRM, emulated resistance independent of V_{in} and V_o:

$$t_1 + t_2 = T_{hf} \Rightarrow \frac{t_1}{T_{hf}} = \frac{M-1}{M} \quad \Rightarrow R_{em\_bst\_crm} = \frac{2 \cdot L}{t_1 \cdot k}$$

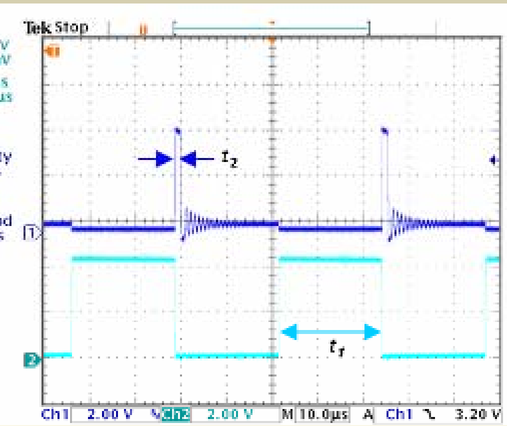
- Similar relationships developed and validated for step down (buck) and step up/down (buck-boost) converters

Discrete Converter Experimental Results

- Near constant resistor emulation over a 10:1 range of input power levels
- Control loss ~15 μW
- Output charges a 4.15 V thin film micro-battery
- Harvesting efficiency greater than 60% at ~100 μW input power.

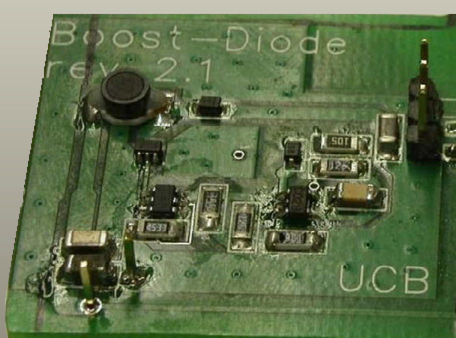


Pulsed Operation

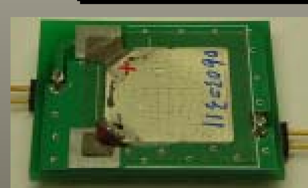


Converter Waveforms

P_{input} (μW)	V_{in} (V)	$R_{emulated}$ (Ω)	P_{out} (μW)	η (%)
112	0.277	687.0	69	61.6
211	0.381	686.9	151	71.6
380	0.508	679.7	287	75.5
642	0.653	664.0	496	77.3
996	0.800	642.7	783	78.6



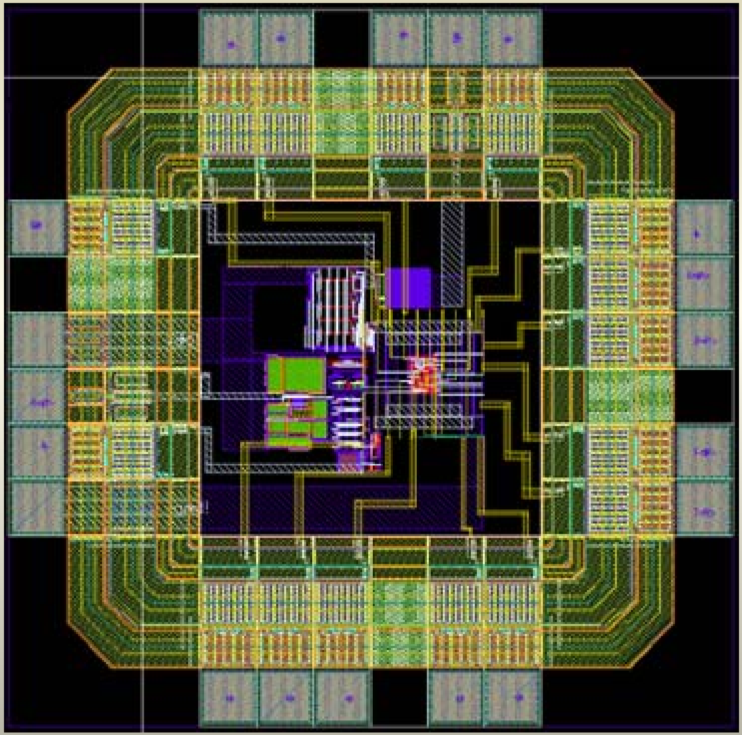
Converter Board



4 V Thin Film Battery (Front Edge Technologies)

Custom Power Management IC

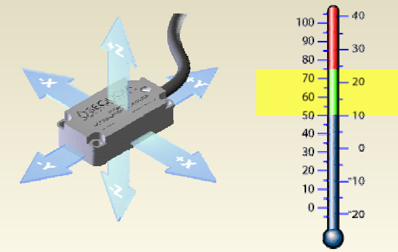
- Developed a custom power management IC *to achieve high efficiency (>70%) down to 1 μW input power*
- Detailed system efficiency optimization analysis performed to design integrated power device, gate drive and on-chip parameter selection
- Designed to drive boost and buck-boost converter topologies from 1 μW to 1 mW input power
- On-chip parameter selection suitable for resistor emulation from 100 Ω to 10 kΩ
- Expected harvesting efficiencies from 70% to 90%
- Shutdown power consumption of 500 pW with restart time of 1 ms.



CAD image of custom IC currently in fabrication in a 0.35μm CMOS process

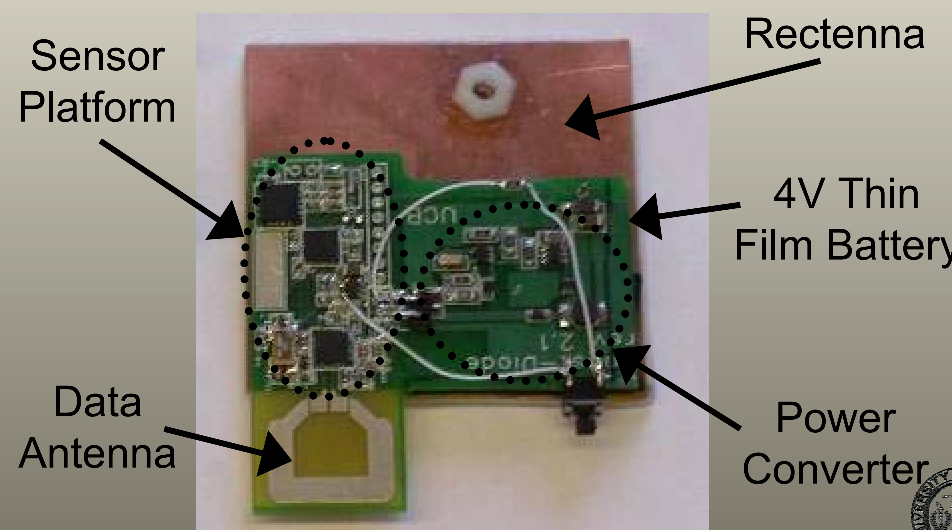
Application Example:
Low duty cycle patient health monitoring sensors

- Patients with physical or cognitive disabilities or other health concerns often need to be monitored for extended periods of time in a controlled environment
- Developed a non-invasive, low-maintenance, wireless platform for continuous, low duty cycle operation
- RF Power: used 6cm x 6cm, dual linear polarized, 2.45 GHz rectenna with resistor emulation boost converter and 4.2 V thin film 400 μAh battery from Front Edge Technology

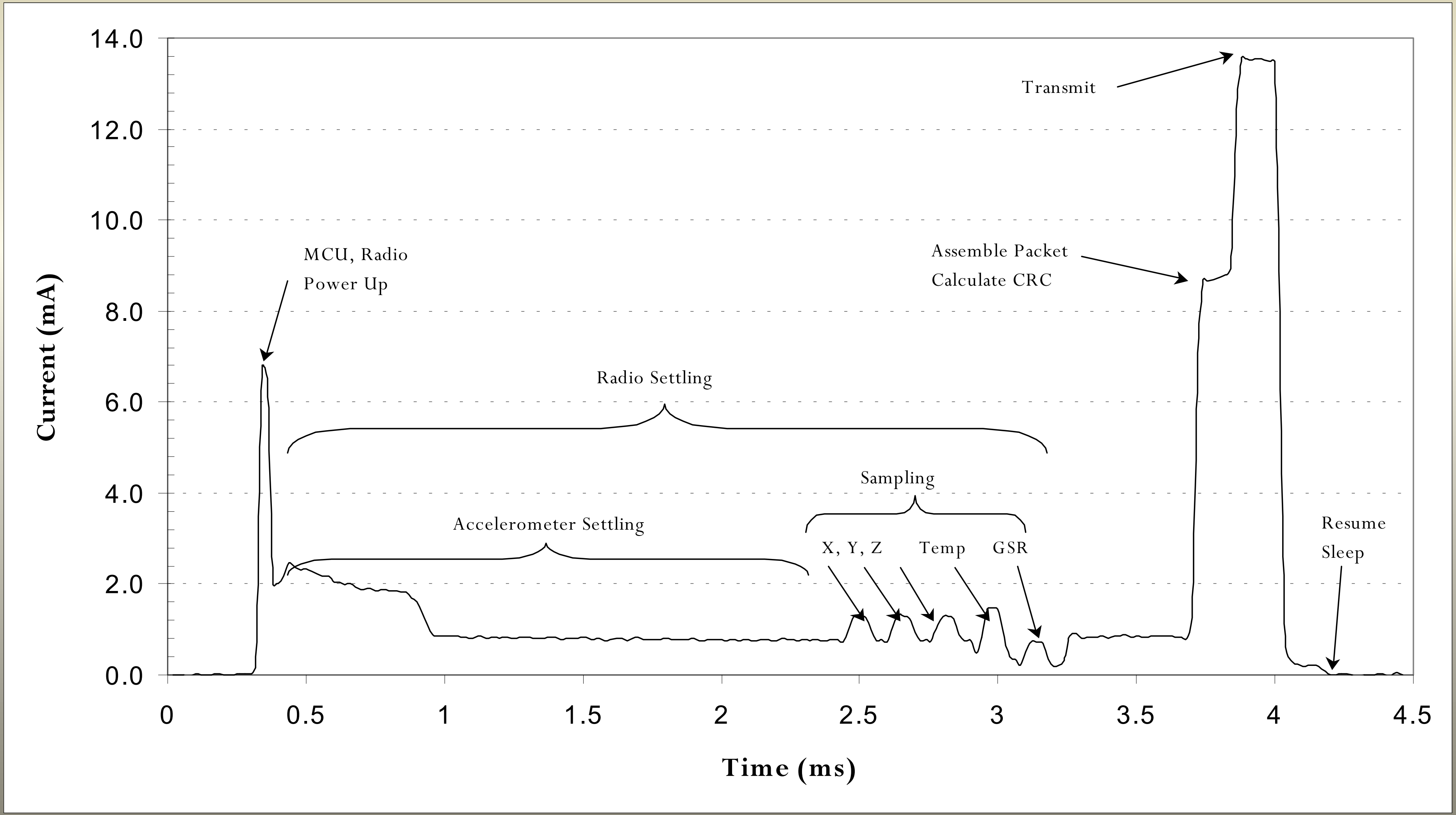


Sensor monitors 3-axis motion & orientation, temperature, skin resistance, input power and stored energy

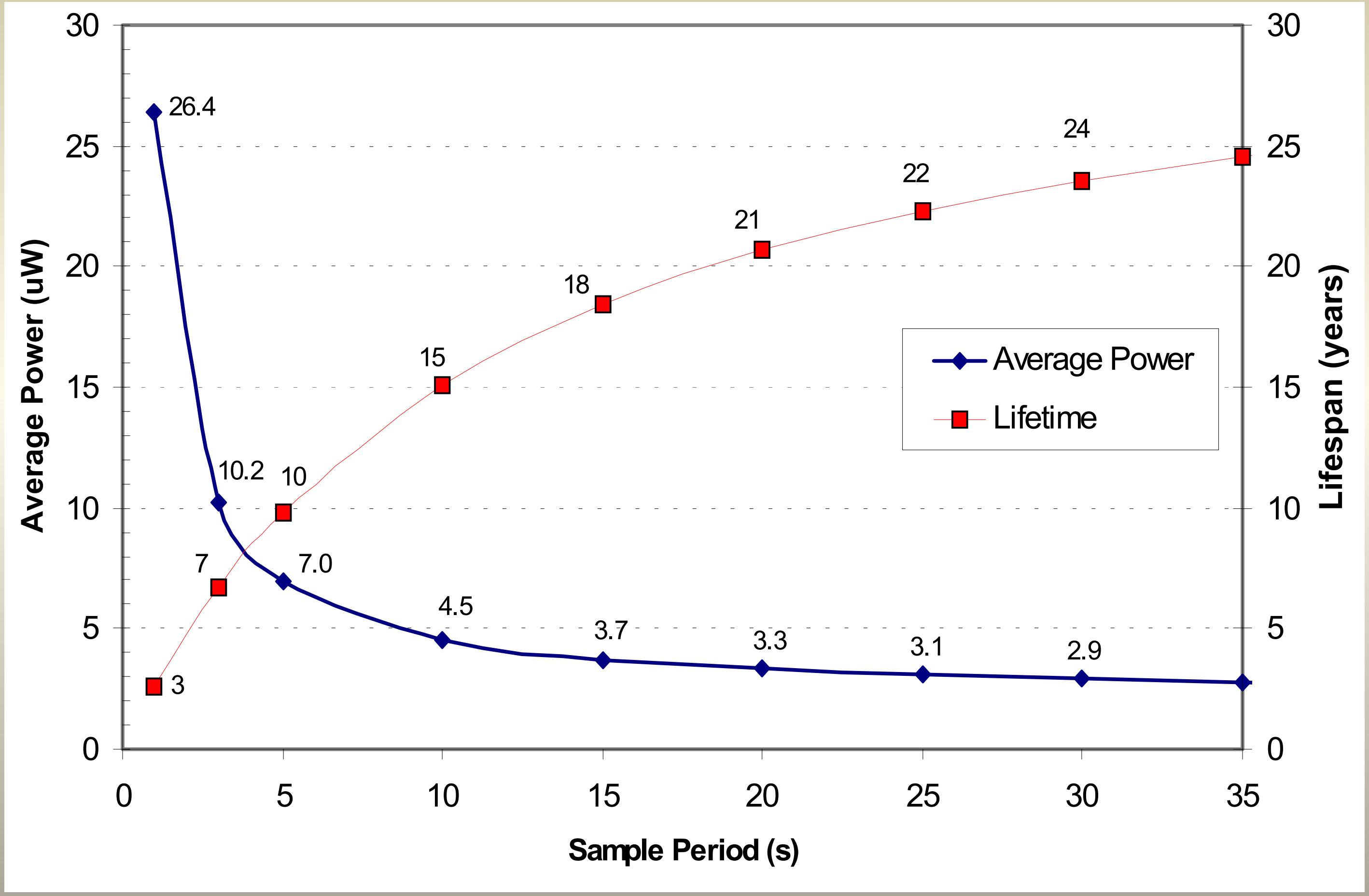
Wireless demo unit requires ***less than 5 μW average power****, transmits ~100 bits every 10 seconds, 10 m range*



Power Usage Profile



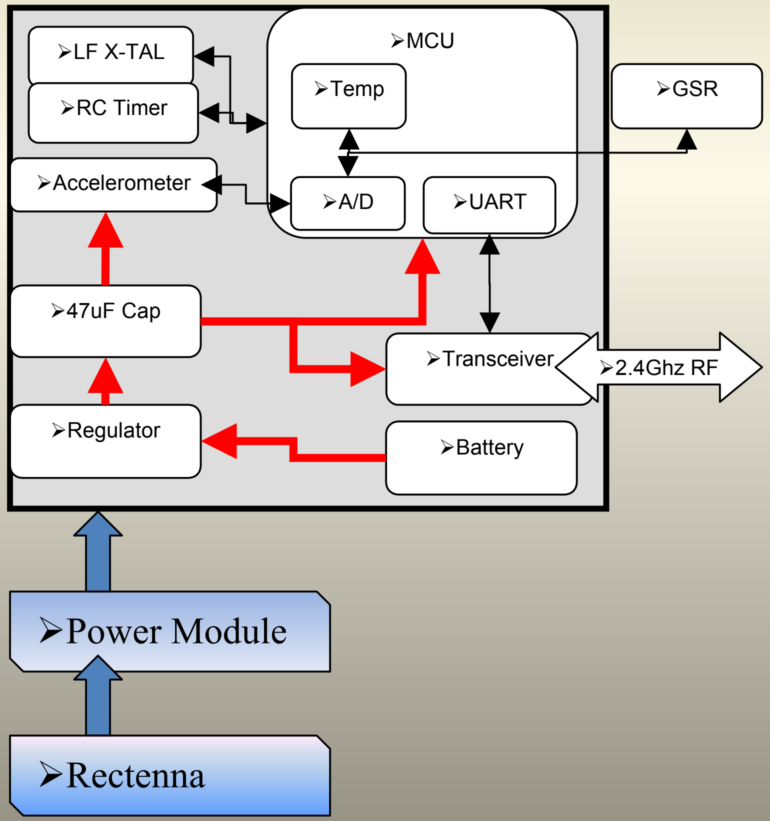
Power Consumption/Lifespan Profile



- power consumption approaches standby power as duty cycle decreases.
- even though TX current is high, average power consumption low due to 'burst' architecture – fast start-up, settling and processing times

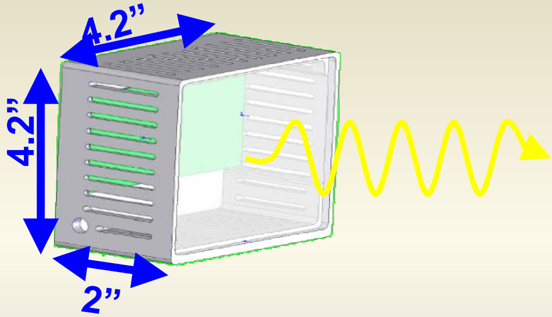
Low-Power Wireless Sensor Overview

- Module acquires data from sensors using onboard ADC, temporarily stores the data, then transmits it at 2.4 GHz to the receiver station
- The receiver can be ~10 m away at 0 dBm (1mW) output power
- The sensor module is controlled by an onboard microcontroller unit (MCU) optimized for low-power operation

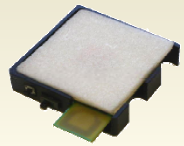


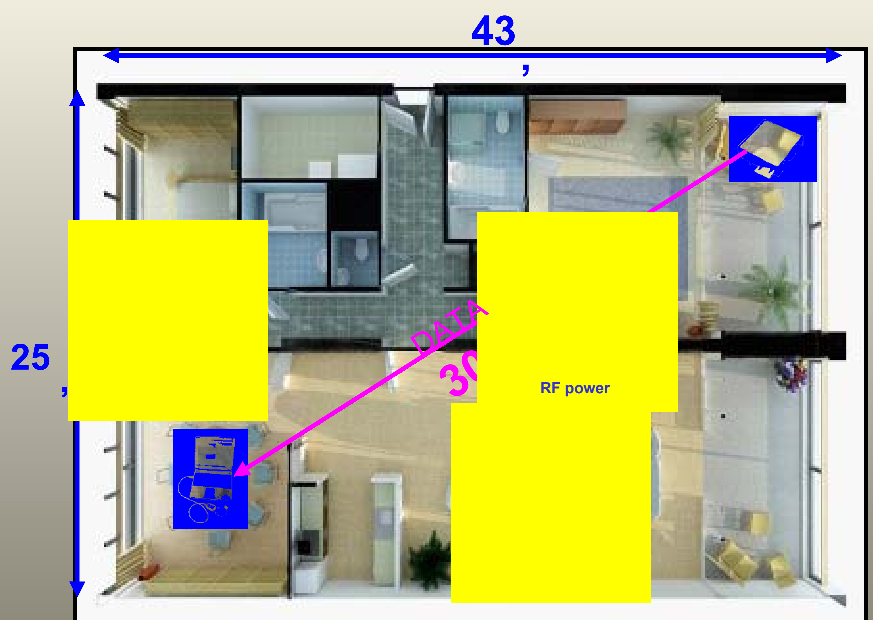
System Hardware Description

Custom RF Transmitter



Sensor unit up to 5 m away

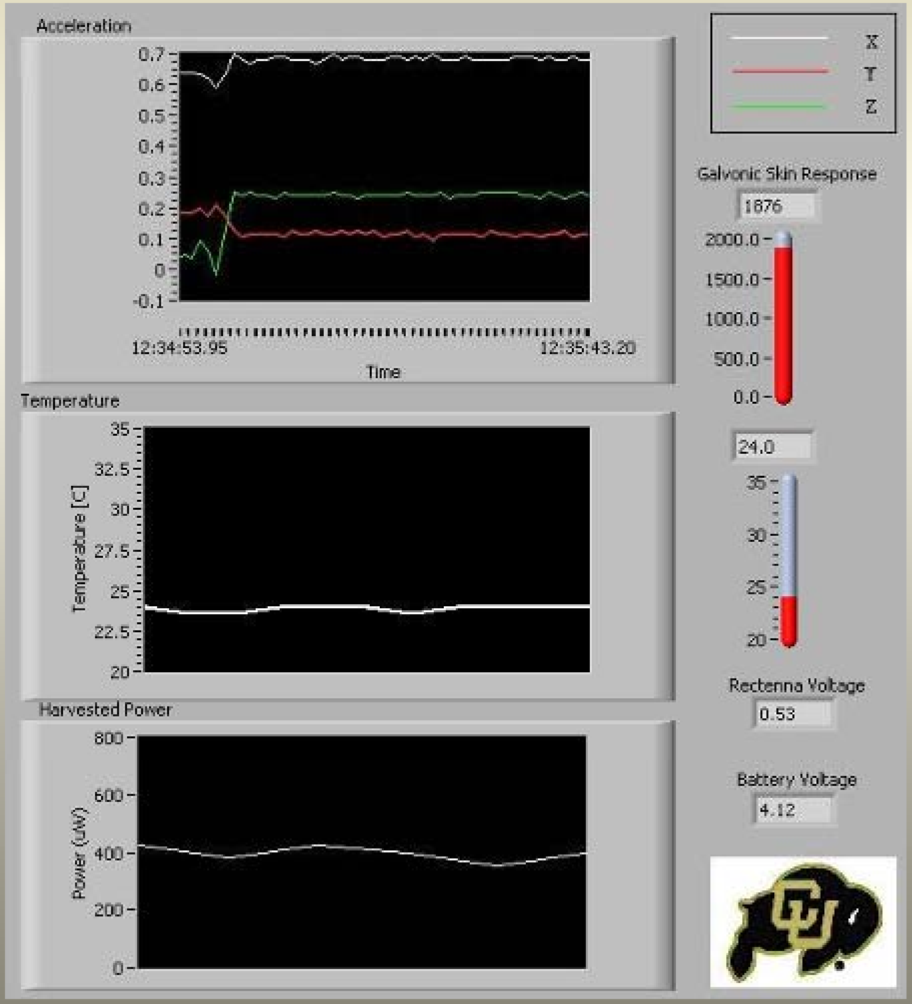




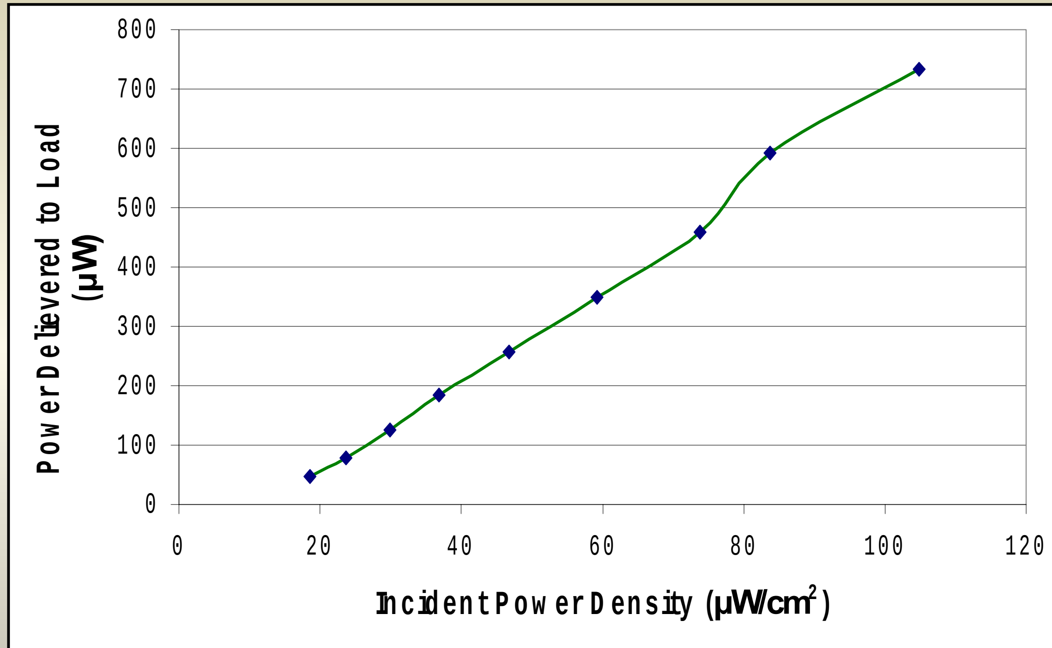
Picture courtesy of: http://www.23art.com/images/Archviz_Pic_L5.jpg

Living area coverage example

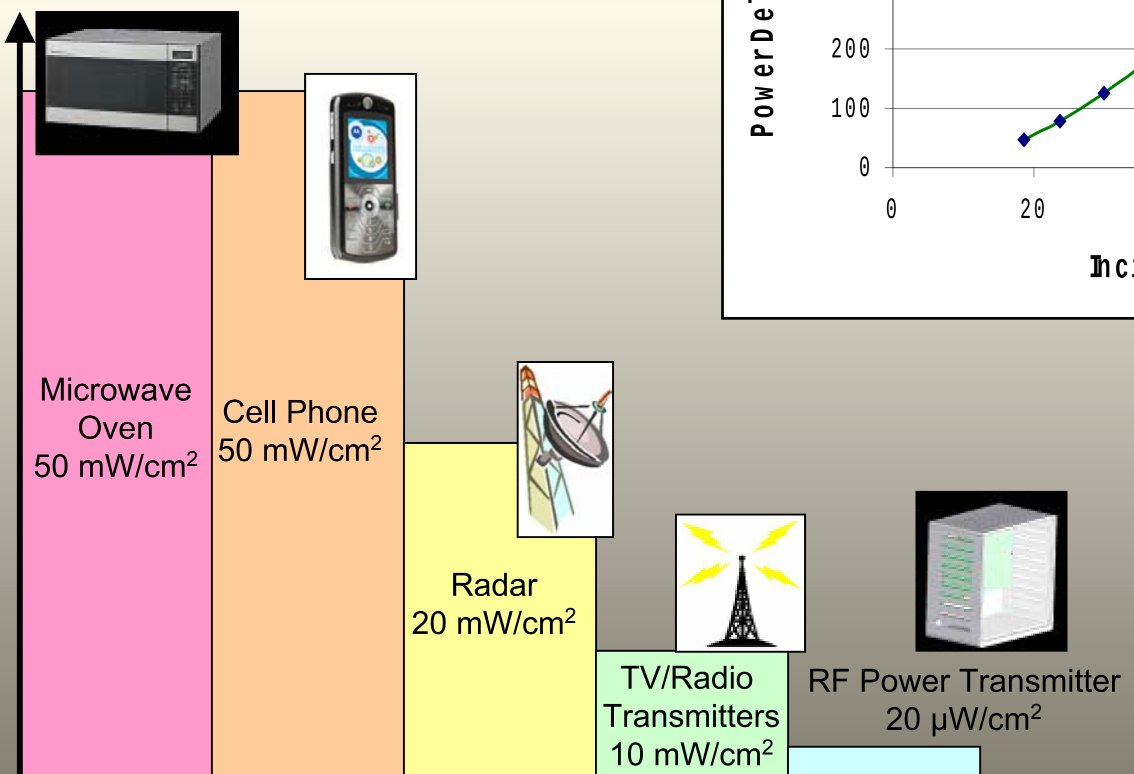
Remote real-time GUI interface



RF Exposure Levels In Everyday Life



Is it SAFE?



- Demonstration unit operates up to 5 m away from RF transmitter
- RF incident power densities up to 3 orders of magnitude below levels possible in everyday life

Applications to Date

- Broadband harvesting and RF power absorption in a dense unsafe transmitter environment
- Piezoelectric tomographic aircraft health monitoring for microcorrosion
- Powering of sensors in water pumps installed behind concrete walls
- Powering of low maintance human health monitoring devices
- Powering drone satellite from host satellite through directive beaming
- Recycling side-lobe power in satellite transmit antennas using deployable rectenna arrays.

Application Characteristics

	Power	Size	Frequency	Polarization
Broadband Harvesting	High	Large	2-18 GHz	Arbitrary
Aircraft Health	Medium	Medium	10 GHz single frequency	Linear
Water Pumps	Low	Small	ISM Band narrowband	Dual Linear
Human Health	Low	Small	2.45 GHz narrowband	Dual Linear
Satellite Powering	High	Large	Single Tone	Linear
Satellite Harvesting	High	Large	Transmitter Dependant	Dual Circular

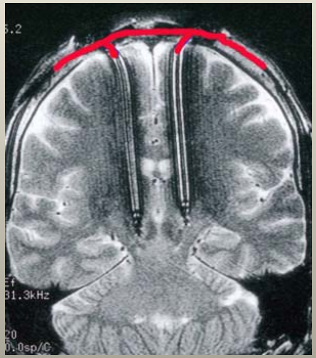
Other Applications Currently Under Investigation

Wireless switch for improved accessibility

Powering of wireless devices indefinitely

Eliminate need to replace batteries

Larger-area “wall-paper” for ambient radio-wave energy recycling



Maintenance-free biological sensors

Conclusions

- Basic concepts for RF power patented over 100 years ago by Tesla, including wireless transmission of energy, storage of energy over time and power and load management on a receiving device
- RF and power groups at UC-Boulder have been researching technologies and developing practical solutions for wireless power delivery and reception since the mid 1990s
- Demonstrated solutions ranging from sub-microwatts to hundreds of milliwatts, linear and circular polarization, continuous and pulsed loads, rigid to flexible substrates
- Currently building an industry sponsored wireless power research center with applications ranging from consumer, commercial and military to biomedical