Reliability Despite Ultra-low Power — The Ultimate Quest in AWSN

Stanford University, January 26, 2004

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http://bwrc.eecs.berkeley.edu

PicoRadio

A Development of Berkeley Wireless Research Center

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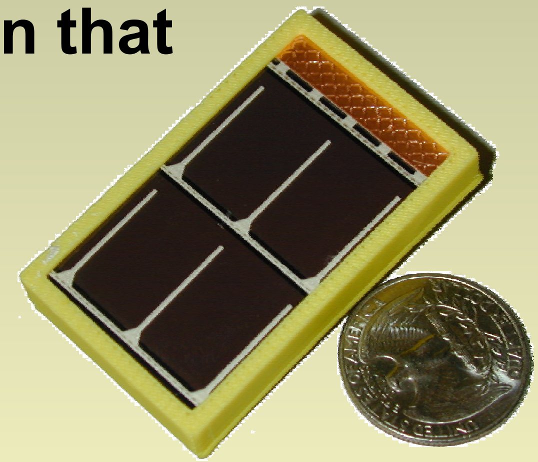
"Ambient Intelligence" (The Concept)

- An environment where technology is embedded, hidden in the background
- An environment that is sensitive, adaptive, and responsive to the presence of people and object
- An environment that augments activities through smart non-explicit assistance
- An environment that preserves security, privacy and trustworthiness while utilizing information when needed and appropriate

Fred Boekhorst, Philips, ISSCC02

The Implementation Challenge

Meso-scale low-cost wireless transceivers for ubiquitous wireless data acquisition that



- are fully integrated
  - –Size smaller than 1 cm^3
- minimize power/energy dissipation
  - – Limiting power dissipation to 100 μW enables energy scavenging
- support low data-rates (< 100 kBit/sec)
- and form self-configuring, robust, ad-hoc networks

Still valid, but pushing the limits ever further

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Energy Sources

Power Source	P/cm^3 ($\mu W/cm^3$)	E/cm^3 (J/cm^3)	P/cm^3/yr ($\mu W/cm^3/Yr$)
Primary Battery	-	2880	90
Secondary Battery	-	1080	34
Micro-Fuel Cell	-	3500	110
Ultra-capacitor	-	50-100	1.6-3.2
Heat engine	-	3346	106
Radioactive(^{63}Ni)	0.52	1640	0.52
Solar (outside)	15000	-	-
Solar (inside)	10	-	-
Temperature	40	-	-
Human Power	330	-	-
Air flow	380	-	-
Pressure Variation	17	-	-
Vibrations	200	-	-

Courtesy Shad Roundy (ANU and UCB)

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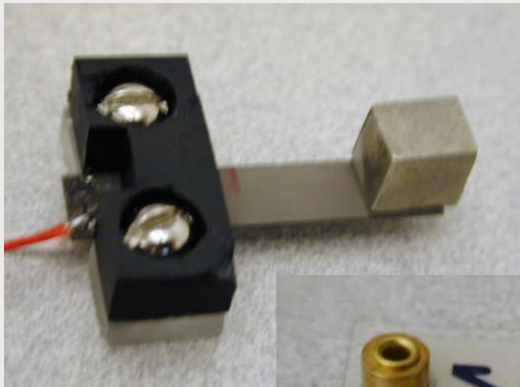
Practical Means of Energy Scavenging

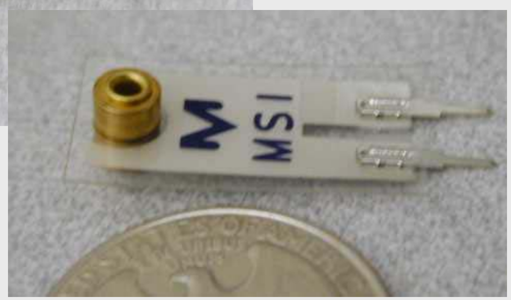
Piezoelectric bi-morphs

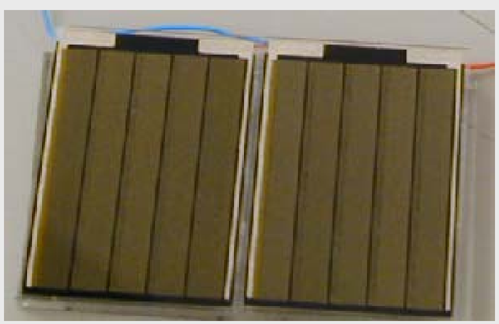


PZT

90 $\mu W/cm^3$

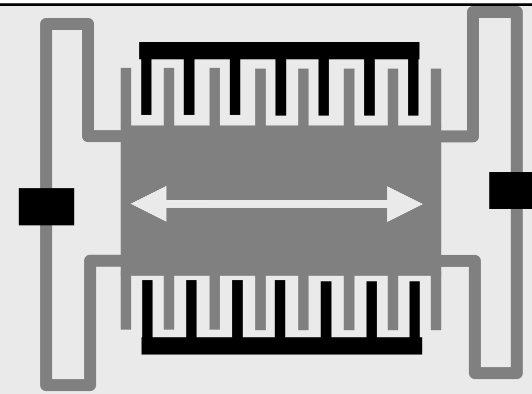
PVDF

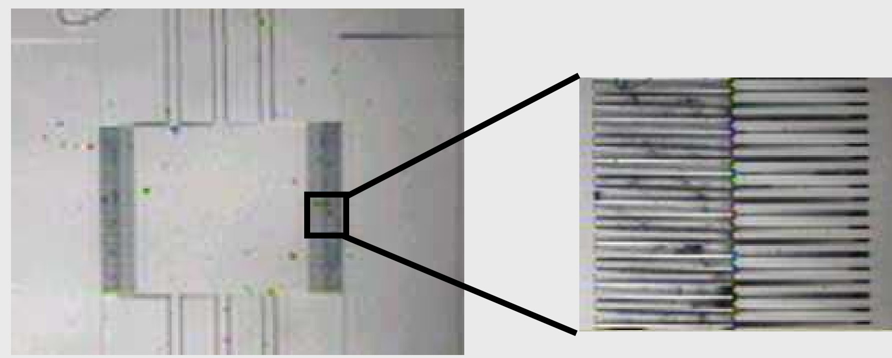




Photovoltaic

10-1500 $\mu W/cm^2$



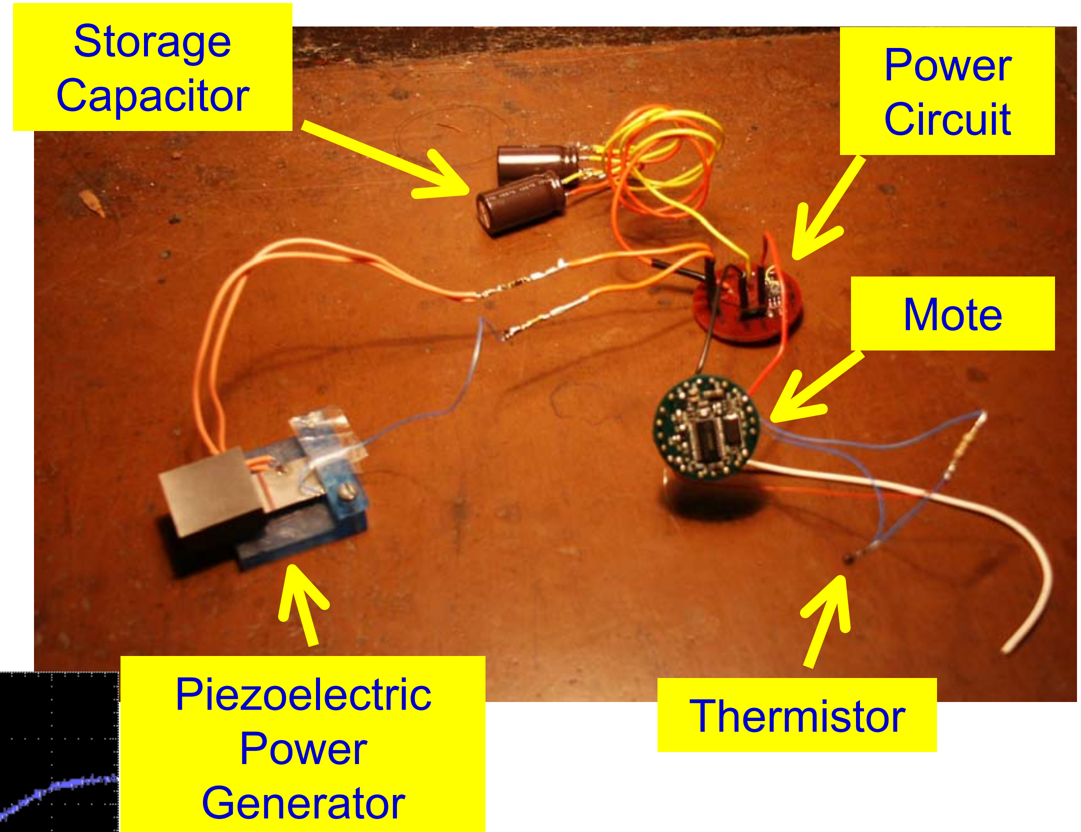


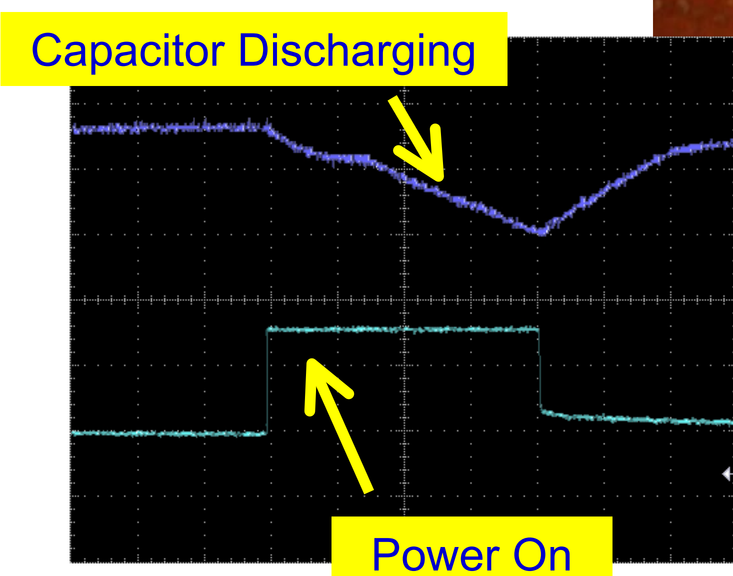
Capacitive converter using MEMS micro-vibrator

30 $\mu W/cm^3$ (on microwave oven)

[Shad Roundy (IML,UCB)]

Vibrational energy from stairs





- 3 people running up and down stairs for 30 minutes
- 2 readings sent to basestation

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The road to low-energy, low-cost, small-size
Not wireless as usual!

- **Simplicity rules!**
  - Advanced techniques used in traditional wireless links are not necessarily relevant
- **Standby power the greatest enemy**
  - Average power dissipation, NOT nJ/bit is the crucial metric
  - Monitoring connectivity dominates overall power
  - Leakage dominates digital power
- **Redundancy and randomness as a means to create robustness**
  - Elements and links can and will fail
  - The environment and its conditions change rapidly

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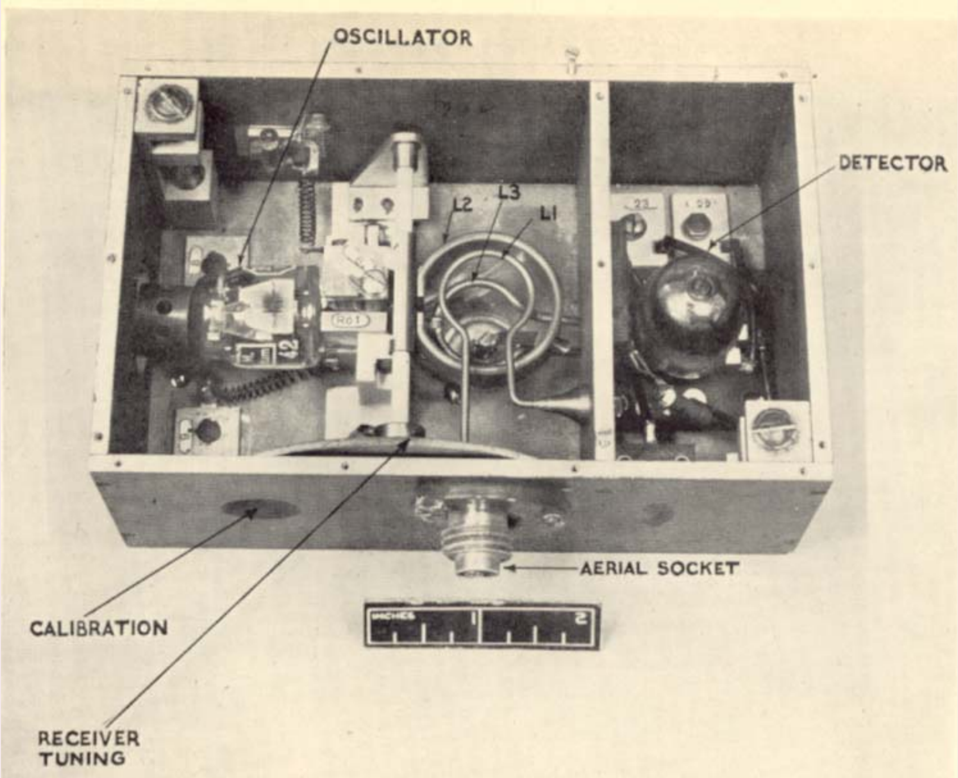
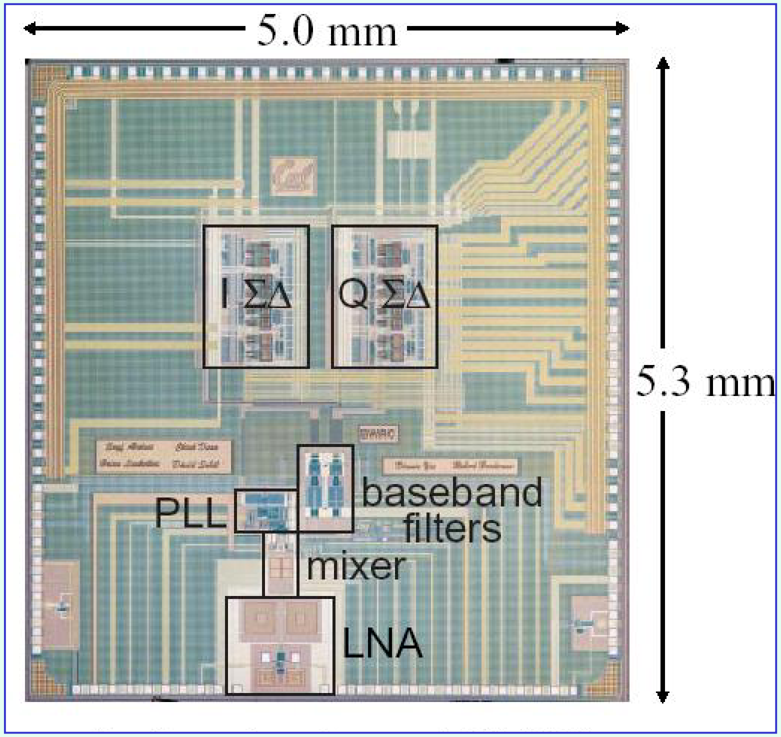
Low-Power RF: Back to The Future
(Courtesy of Brian Otis)



© 1949 - superregenerative
fc= 500MHz
2 active devices
high quality off-chip passives - hand tuning

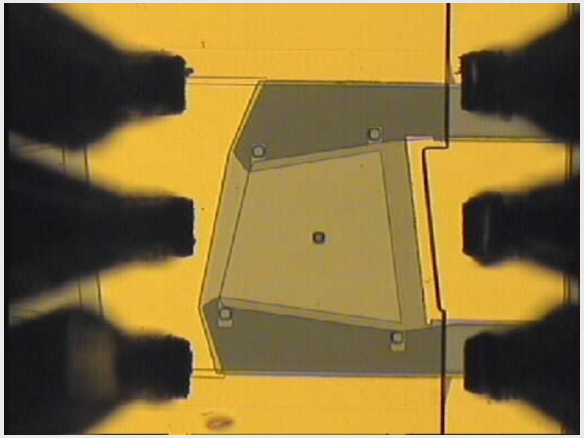
© 2000 - Direct Conversion
f_c= 2GHz
>10000 active devices
no off-chip components



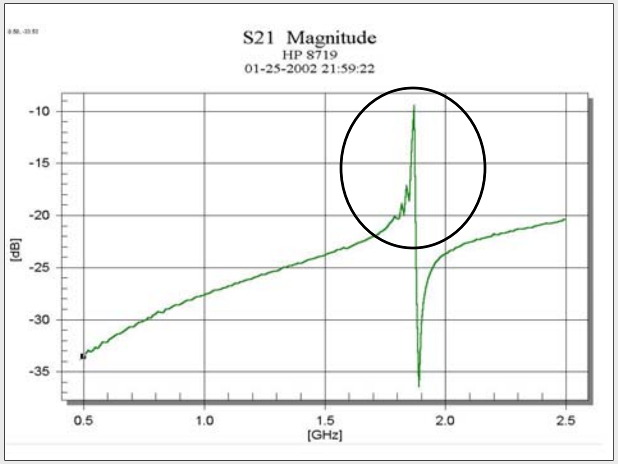
D. Yee, UCB

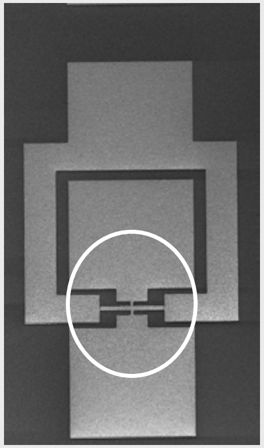
RF-MEMS: The Opportunity

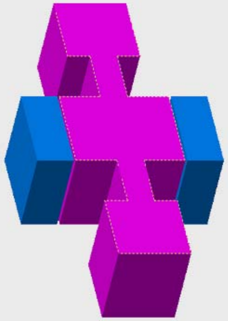
Passive micro-resonators
- High Q (> 1000)
- High Frequency (> 1 GHz)
- Very Small
- Potential for integration



Thin-Film Bulk Acoustic Resonator
(FBAR [Ruby,ISSCC01])
Q > 1000 @ 2 GHz



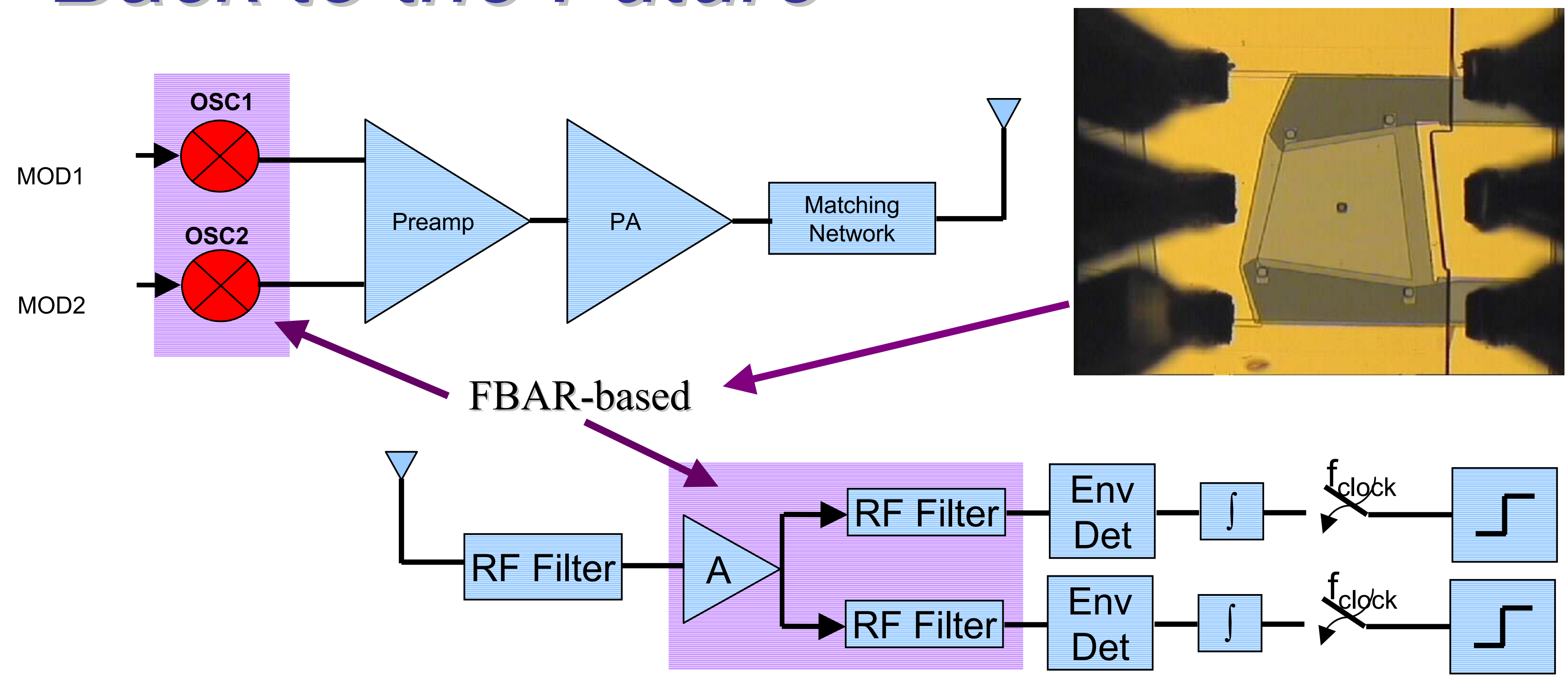




SiGe MEMS Capacitive
Bulk Longitudinal Resonator
(BLR [Bircumshaw01])
Q > 500; f > 100 MHz

Back to the Future

Thin-Film Bulk Acoustic Resonator



- Minimizes use of active components – **exploits new technologies**
- Uses simple modulation scheme (OOK)
- Allows efficient non-linear PA
- Down-conversion through non-linearity (Envelope Detector)
- **Tx and Rx in 1-2 mW range** (when on)

(PicoRadio RF)

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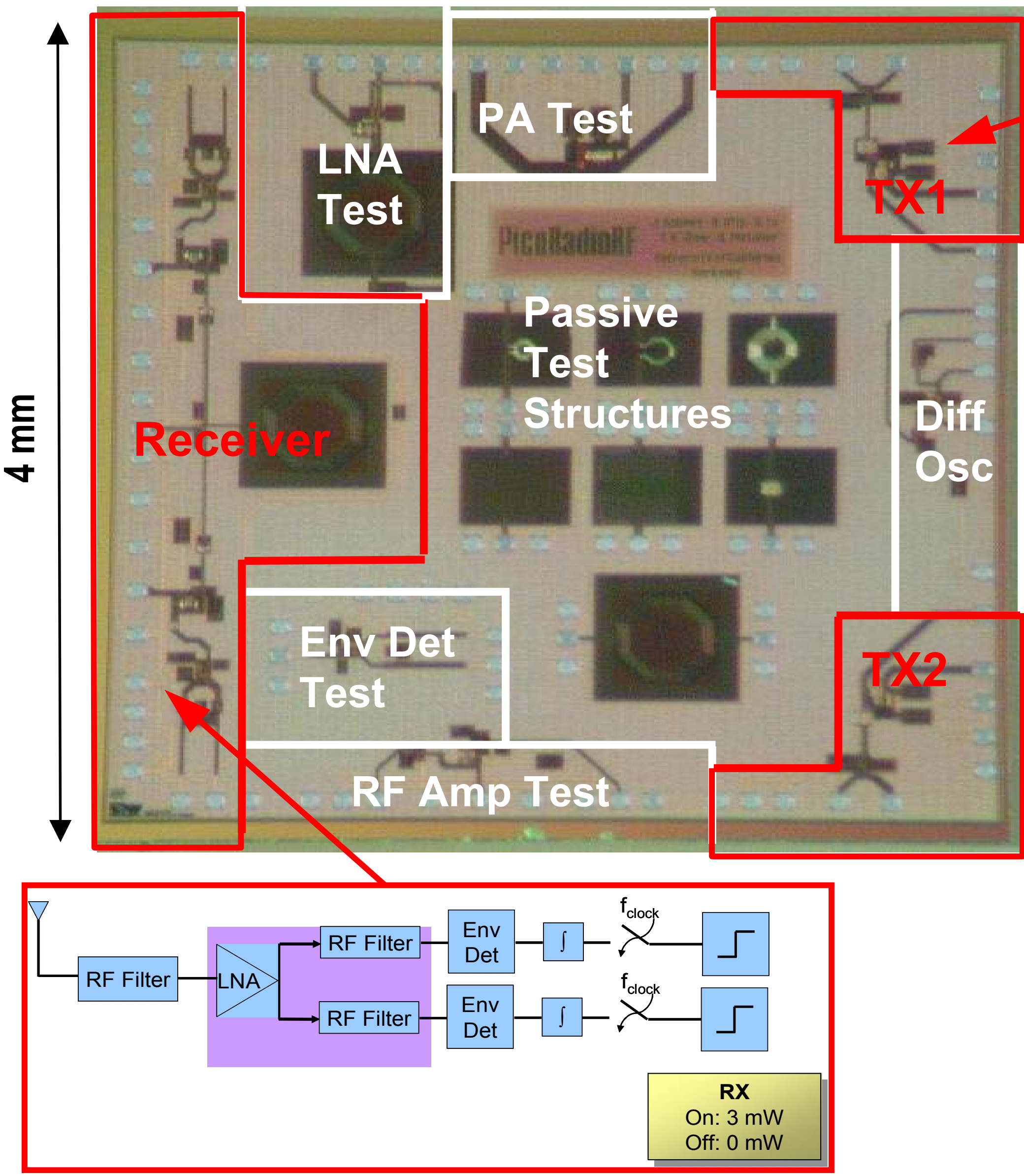
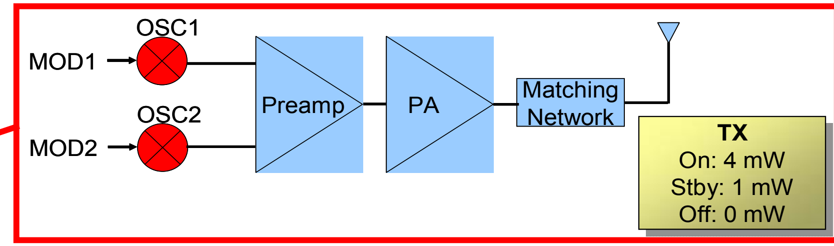
The Incredibly Shrinking Radio





- Technology: 0.13 μm CMOS combined with off-chip FBARs
- Carrier frequency: 1.9 GHz
- 0 dBm OOK
- Two Channels
- Channel Spacing ~ 50MHz
- 10-160 kbps/channel
- Total area < 5 mm^2

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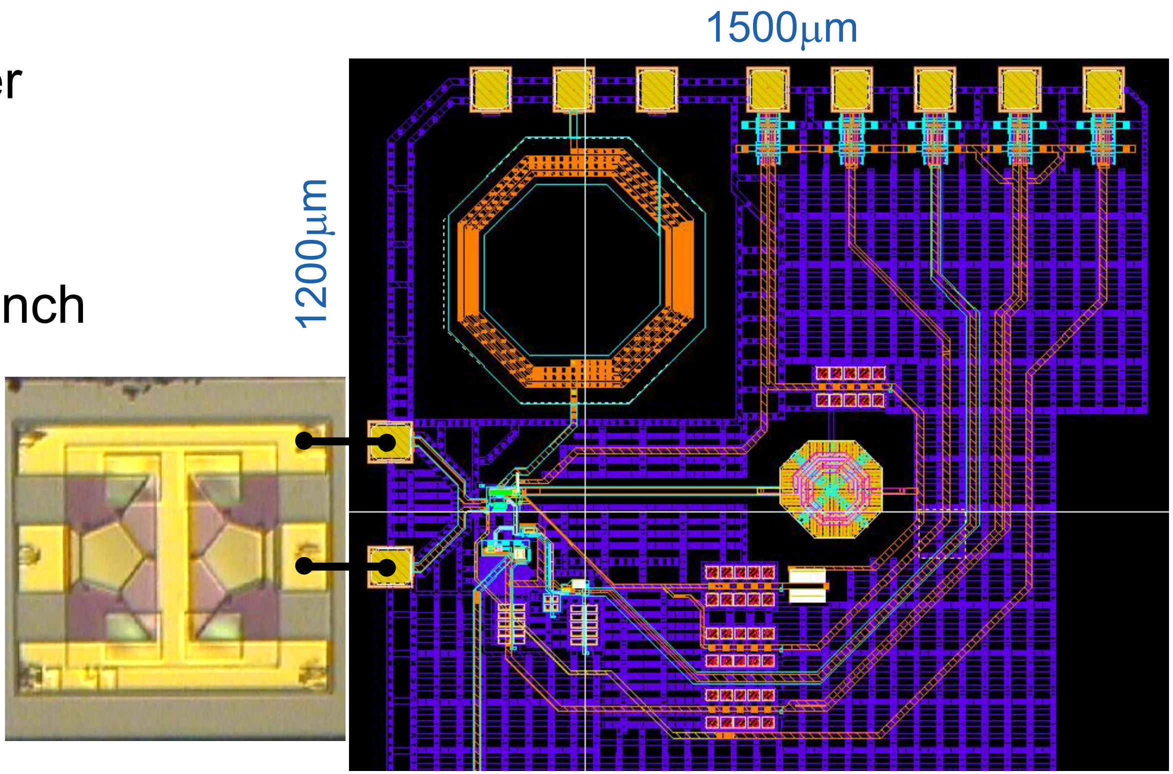
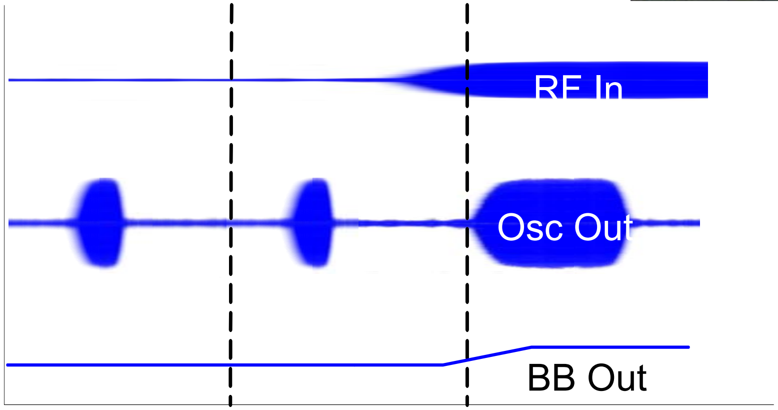
The Return of Superregenerative

- Fully Integrated Receiver Front-end
- 400μA when active (~200μW) with 50% quench duty cycle





(Currently in fab - prototype expected early January)

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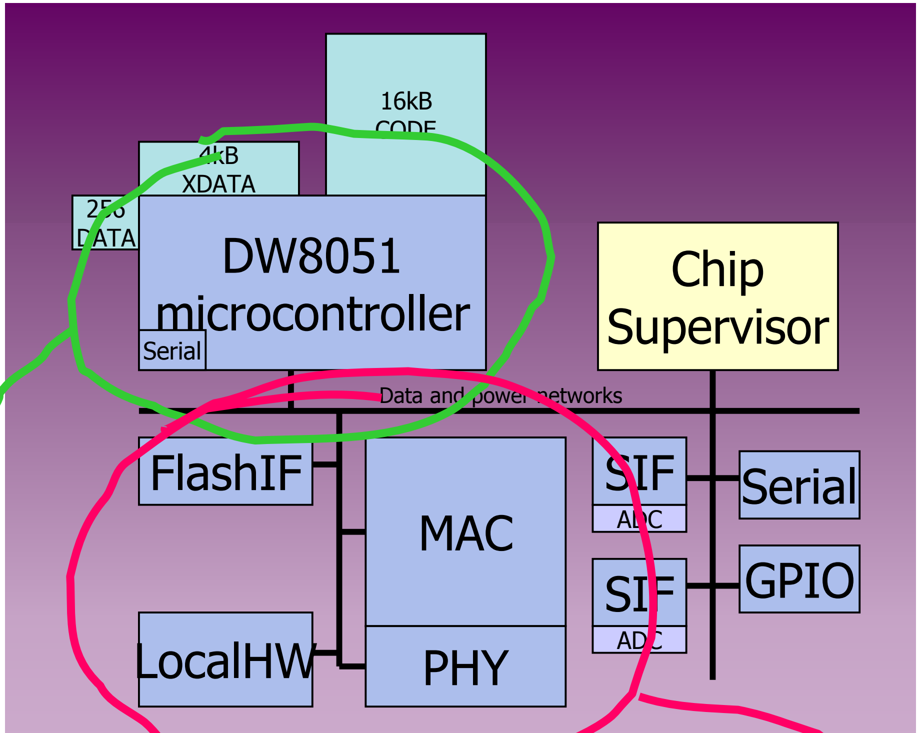
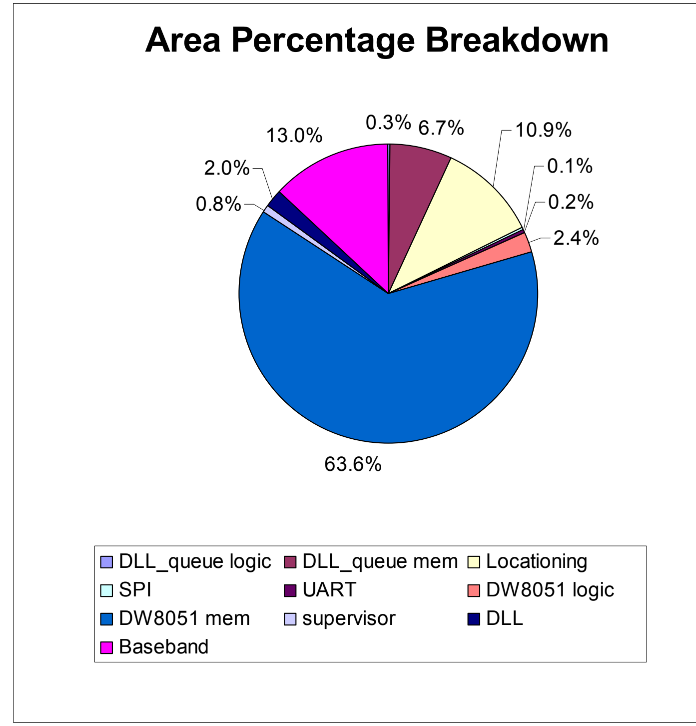
Low-Energy Digital Network Processor





Simplicity rules:

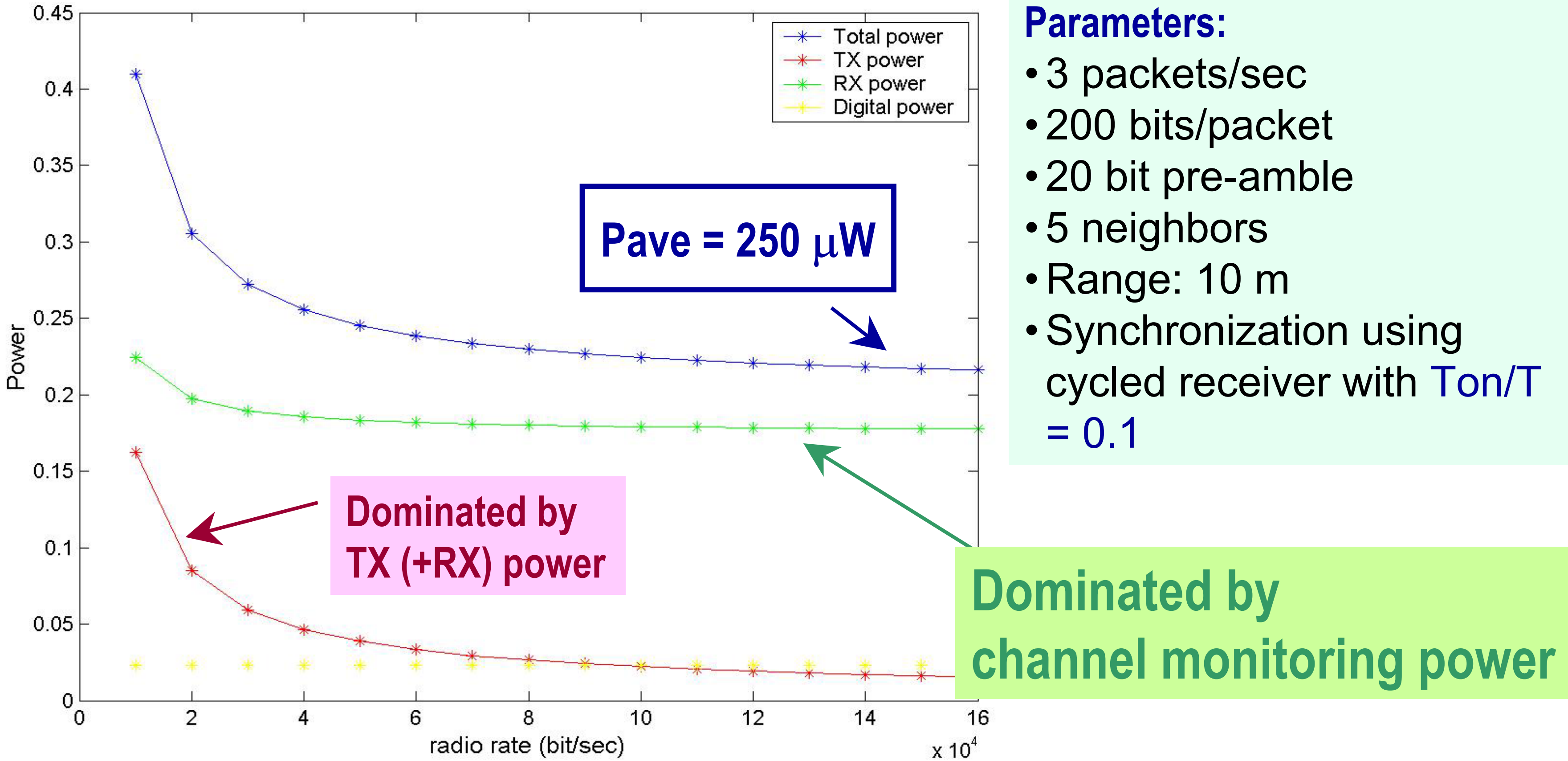
- simplest possible processor
- hardwired accelerators when needed
- lowest possible clock frequency
- operational voltage: 1V (130 nm CMOS)

Area:
- **150 kGates (not including memory)**
- **~ 4 mm^2**

Clock Frequency:
- **on-mode: 16 MHz**
- **standby: 32 KHz**

Power:
- **1mW in full on-mode; < 10 μW in standby**

Standby Power – The Greatest Enemy



Parameters:

- 3 packets/sec
- 200 bits/packet
- 20 bit pre-amble
- 5 neighbors
- Range: 10 m
- Synchronization using cycled receiver with Ton/T = 0.1

Increasing data rate of radio reduces total power dissipation of PicoNode!

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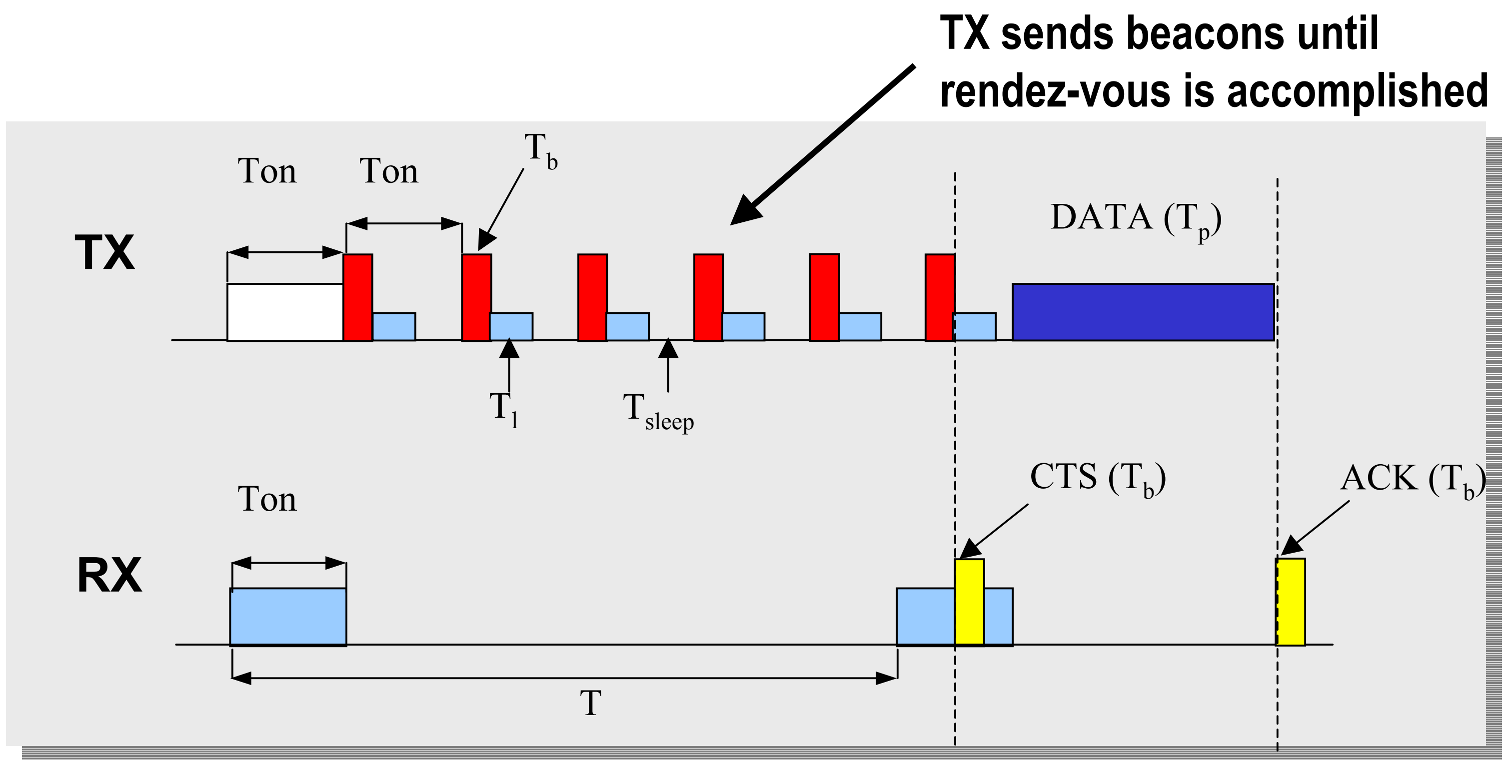
Maximizing the Sleep Time

A pseudo-asynchronous approach: The Cycled Receiver



Allows deep sleep mode of node at the expense of rendez-vous overhead (power and time)

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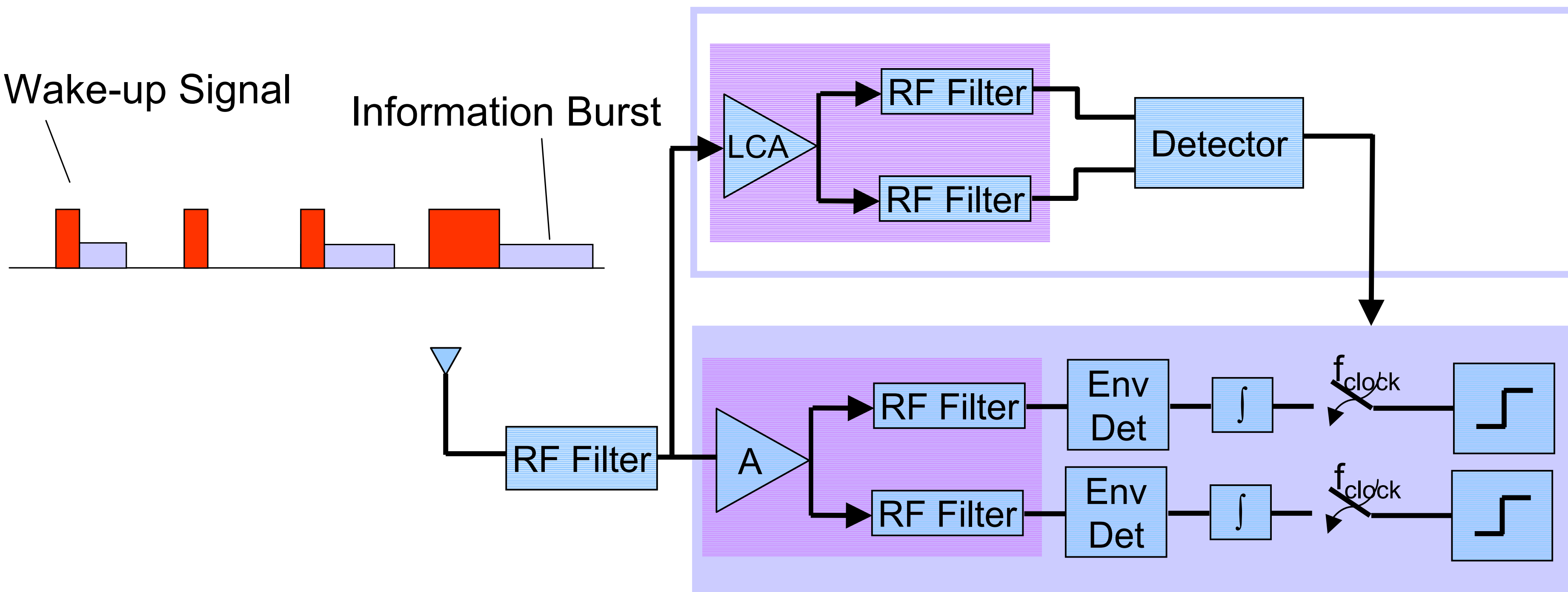
The Reactive or Wake-Up Radio

Wake-up Radio:
Low Gain, Low Sensitivity, Low BER



Shifts Burden to Transmitter
Reduces monitoring power to < 50 μW

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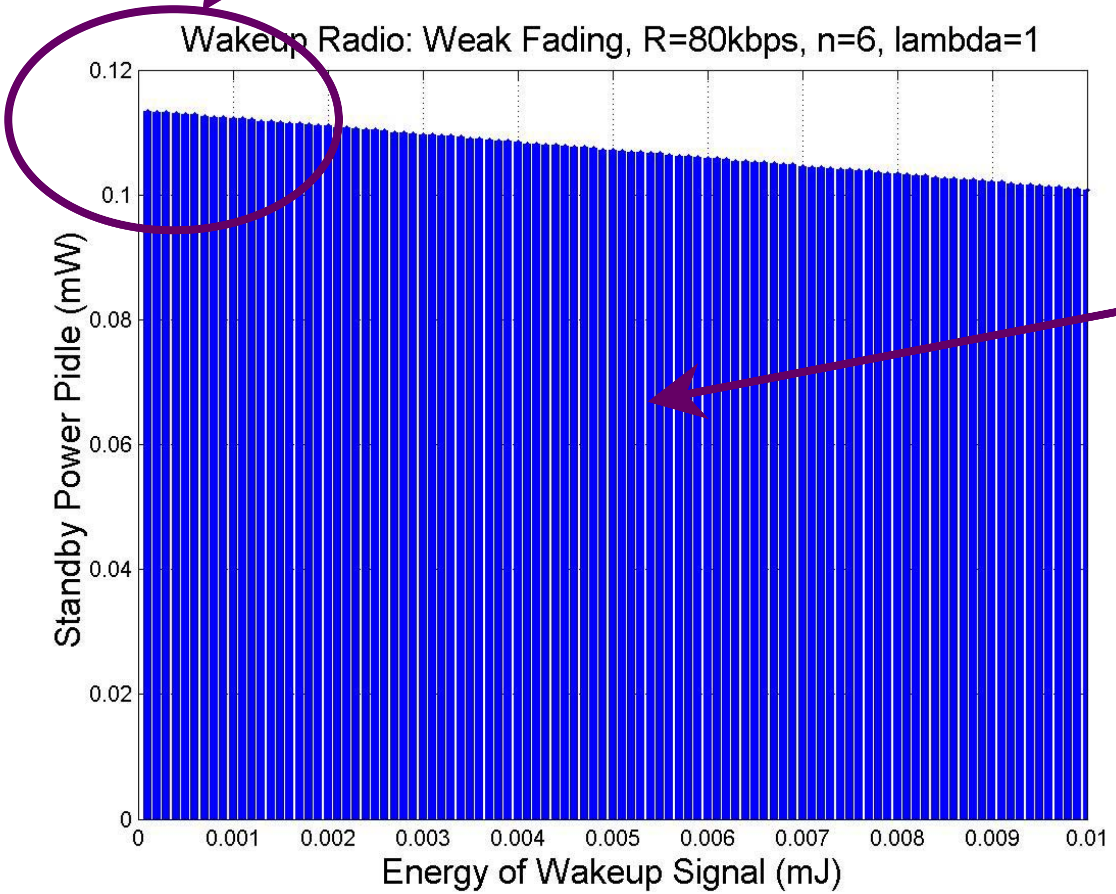
Asynchronous versus. Pseudo-Asynchronous

Wake-up radio of 100 μW suffices



Region of operation where asynchronous wins

(assume 6 neighbors, 1 packet/sec)

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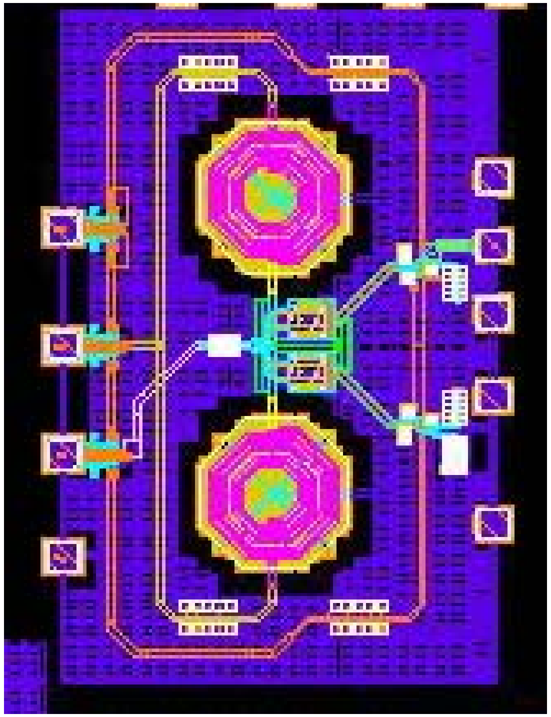
Realizing sub-100 μW carrier-sense

Prototyping building blocks

Example: sub-threshold RF oscillator using integrated LCs (in fab)



Simulated Performance

Supply voltage	**0.5 – 1.2V**
Current consumption	**150µA**
Oscillation frequency	**1.5GHz**
Differential output swing	**150mV (V_{dd}=500mV)**
Phase noise	**-100dBc/Hz @1MHz offset**

Another example: 140 μW 26 MHz wake-up receiver (R. Banna, N. Weste, UNSW)

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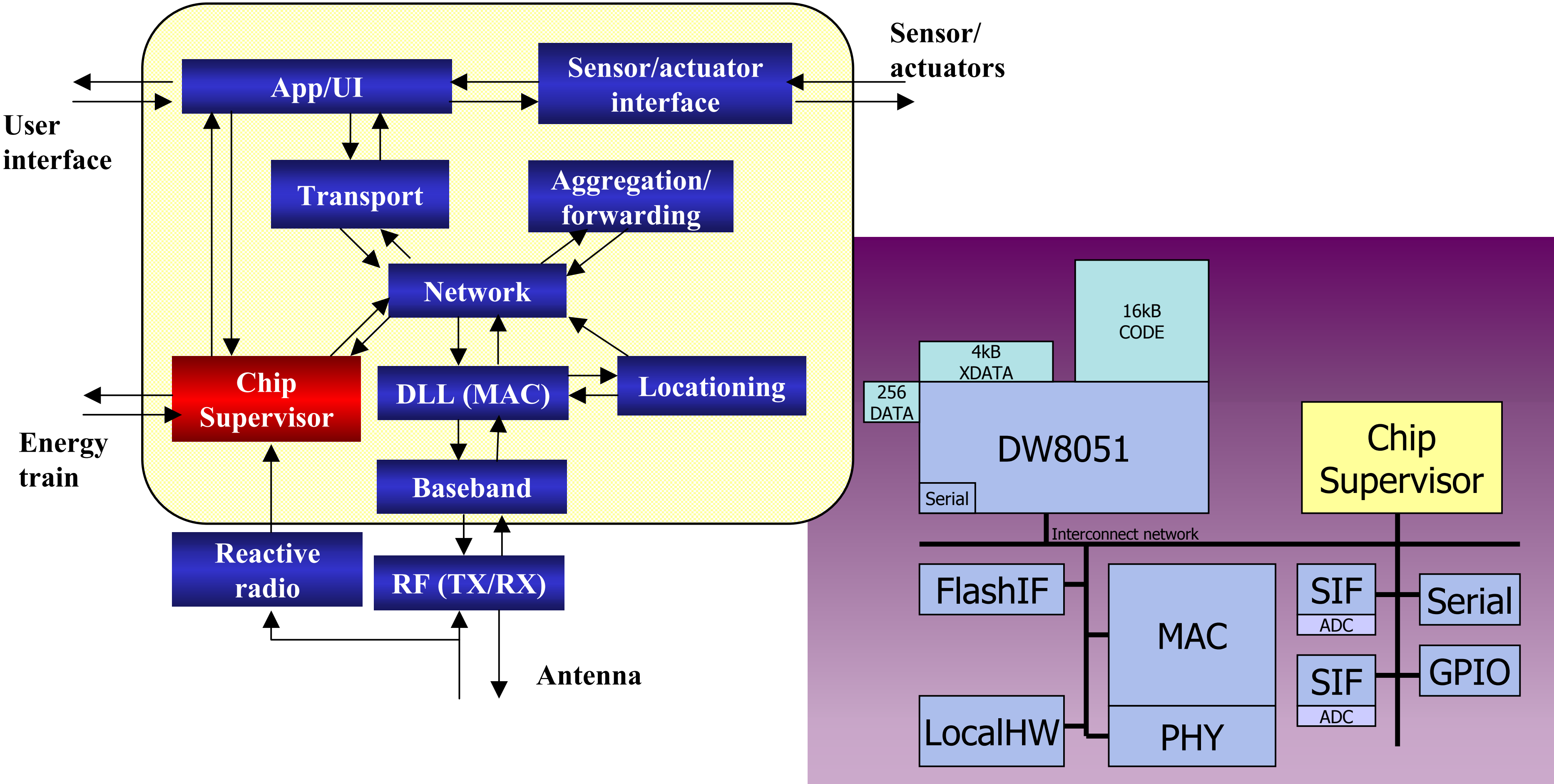
Addressing Leakage: Reactive Digital Network Processor



- Reactive inter- and intra-chip signaling
- Aggressive Use of Power-Domains
- Chip Supervisor Manages Activity

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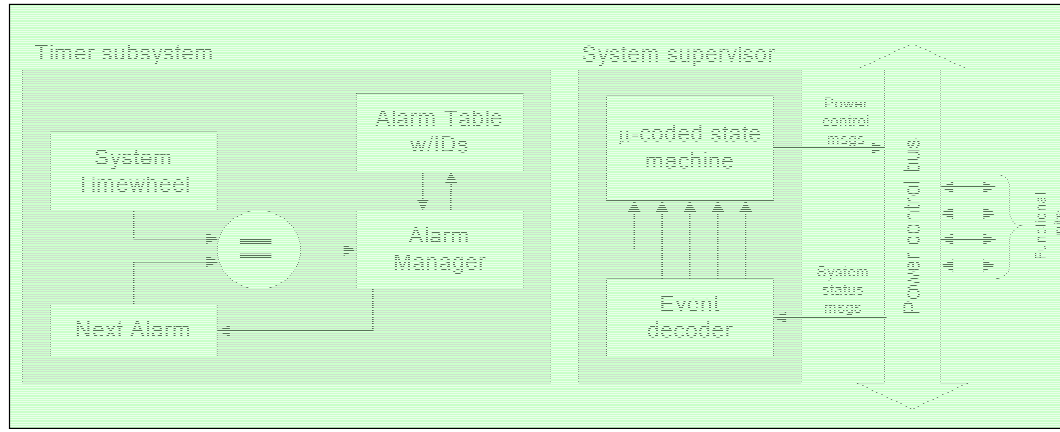
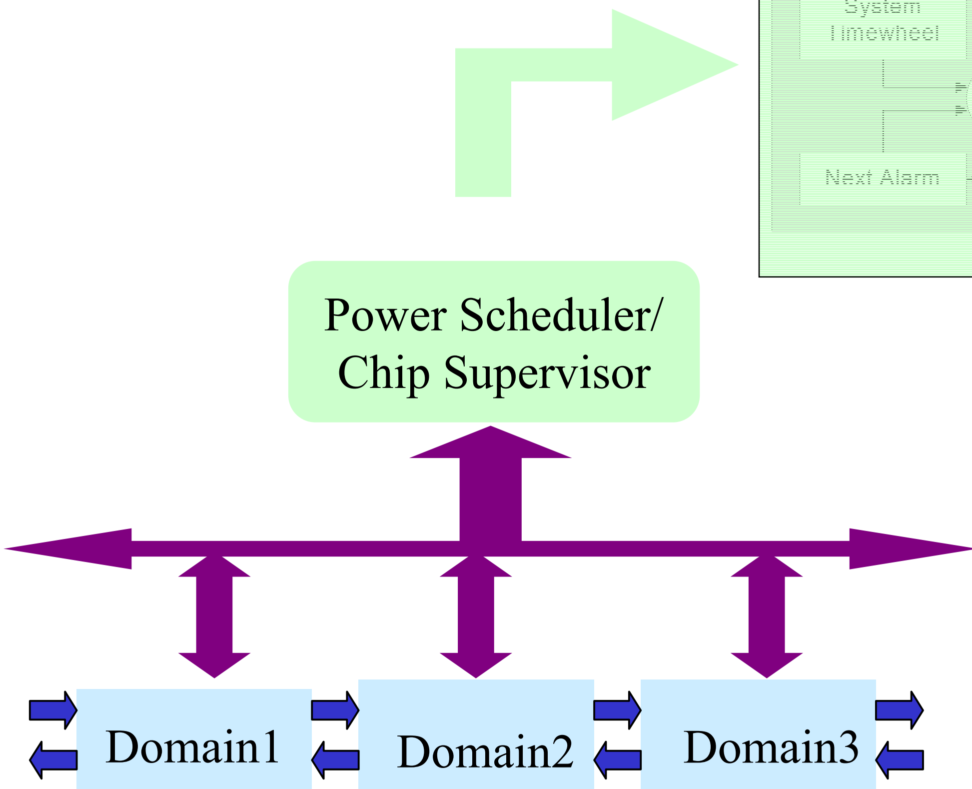
Introducing "Power Domains (PDs)"

Similar in Concept to "Clock Domains", but extended to include power-down (really!).





Chip Supervisor (or Chip O/S)

- **Maintains global state and perspective**
- **Maintains system timers**
- **Alerts blocks of important events**

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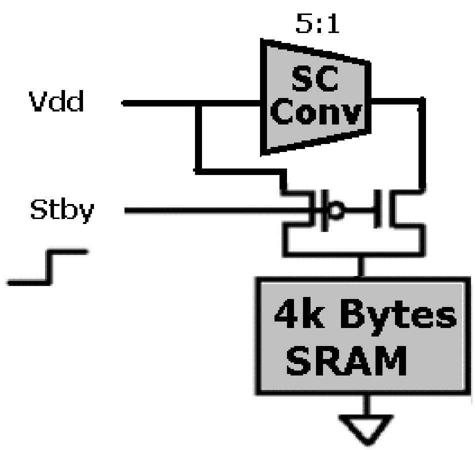
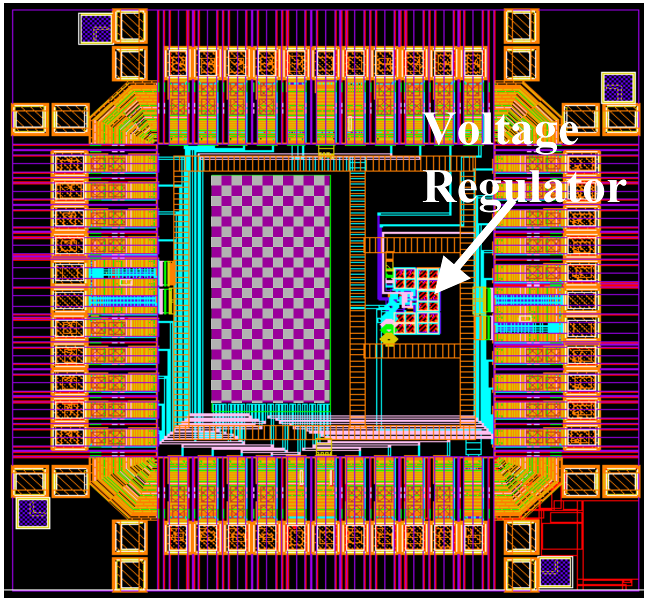
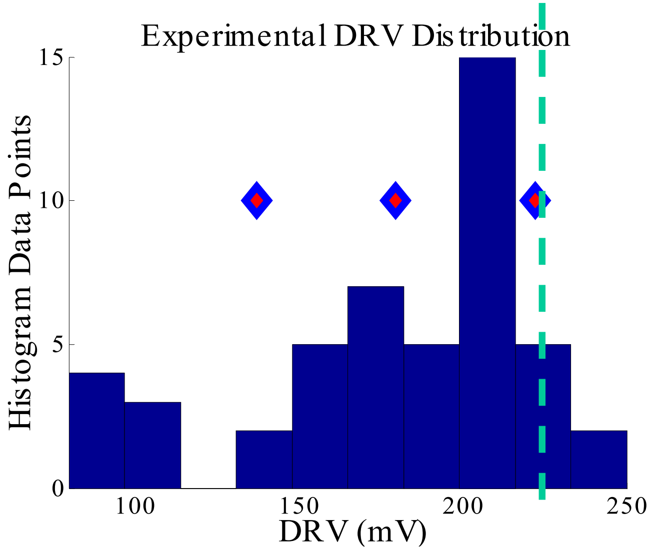
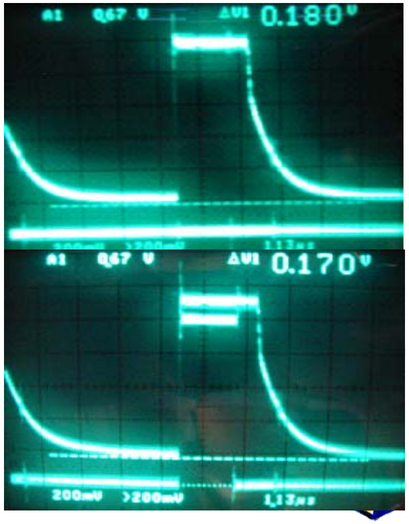
How low in voltage can we go?
"The data retention voltage (DRV)



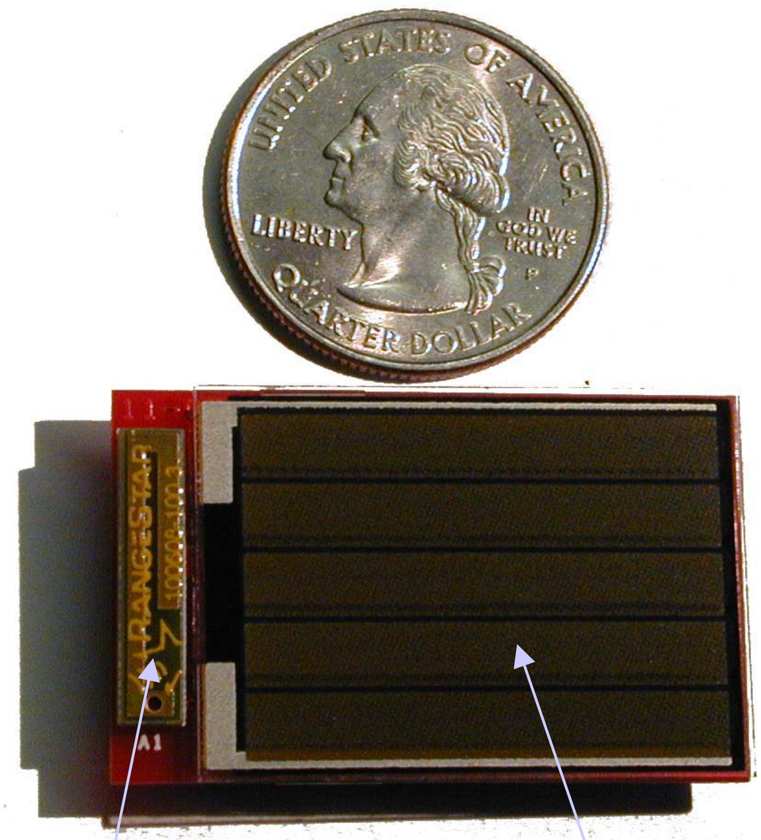






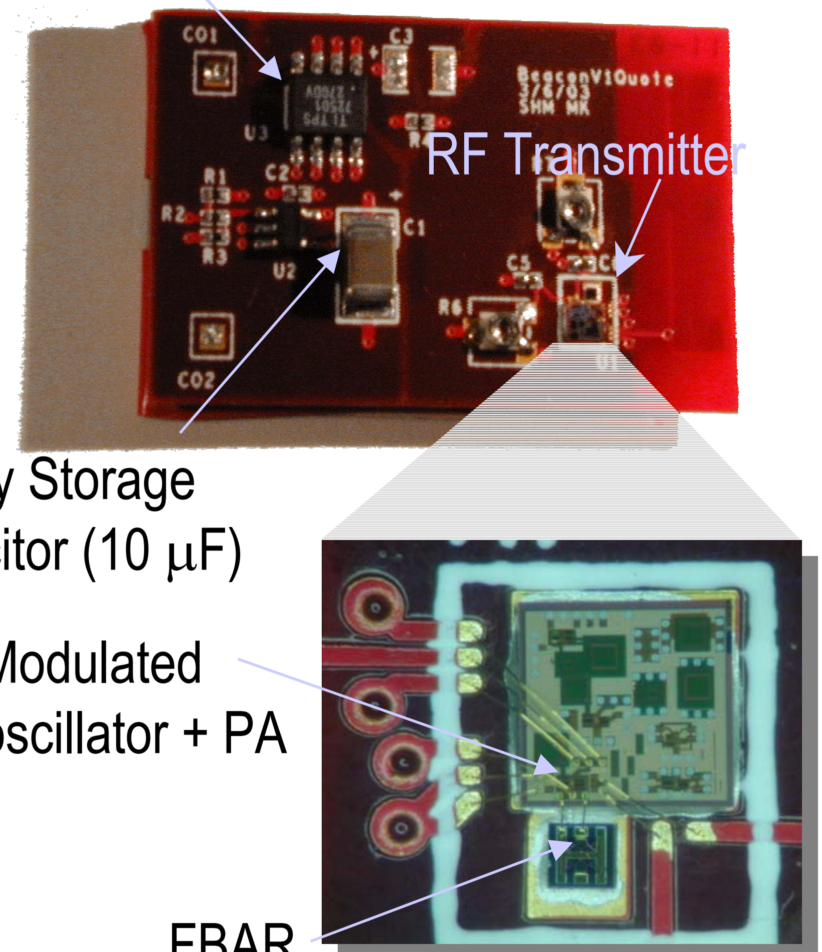
Where Are We Today?

PicoBeacon: An Energy-Scavenging Radio



Antenna (ceramic)

Single solar cell



Regulator

Energy Storage Capacitor (10 μF)

Modulated oscillator + PA

FBAR

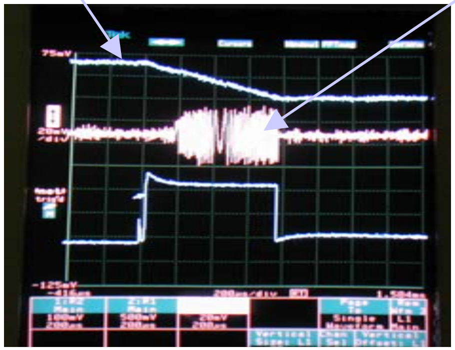
An exercise in miniaturization and energy scavenging

PicoBeacon: An Energy-Scavenging Radio

Voltage over capacitor

Observed RF signal

Radio duty-cycle



Ambient light

Medium light

Intense light †

Light Level	**Duty Cycle**
Low Indoor Light	0.36%
Fluorescent Indoor Light	0.53%
Partly Cloudy Outdoor Light	5.6%
Bright Indoor Lamp	11%
High Light Conditions	100%
Vibration Level	**Duty Cycle**
2.2m/s^2	1.6%
5.7m/s^2	2.6%

† Duty cycle upper-bounded by latency of comparator

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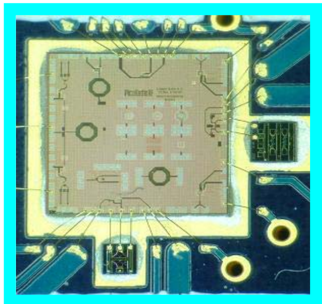
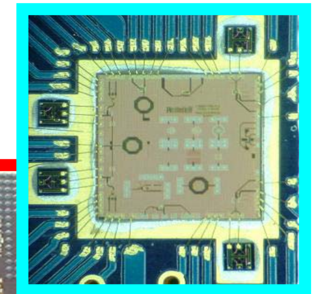
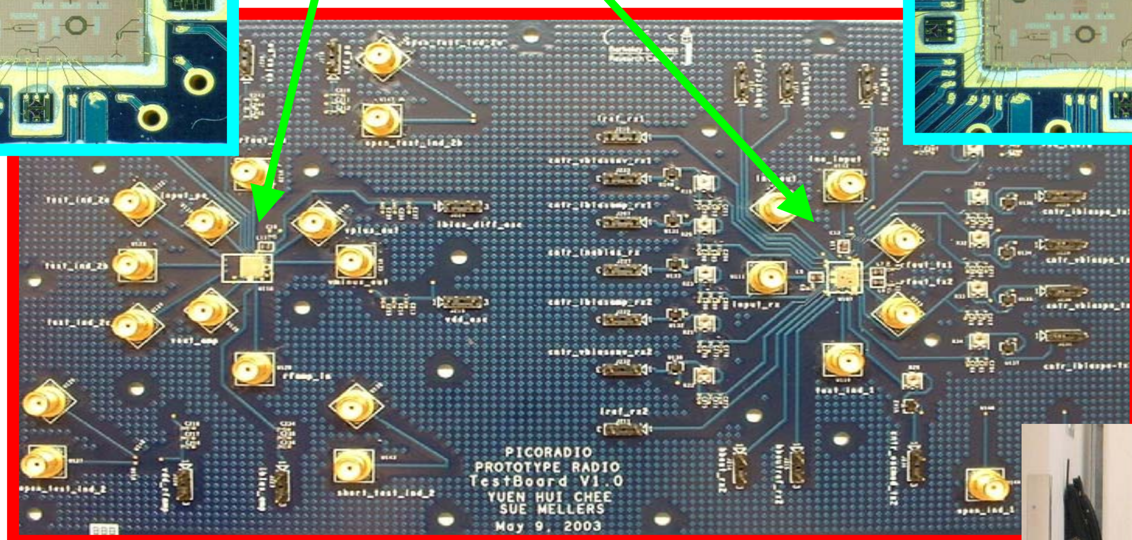
An Operational Wireless Link (2 channels)



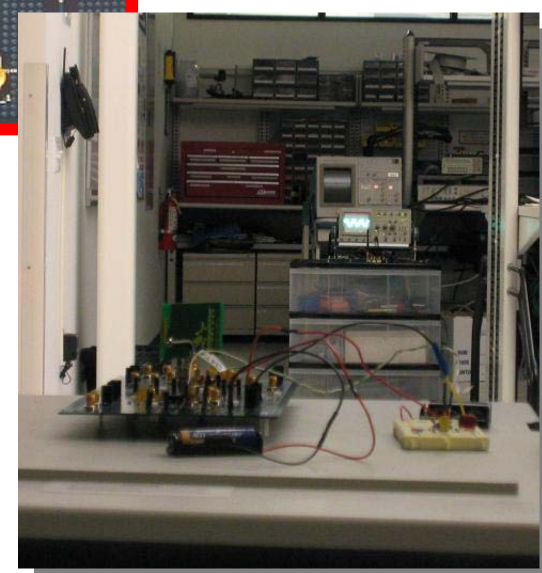
Component Test Chip

Radio Test Chip

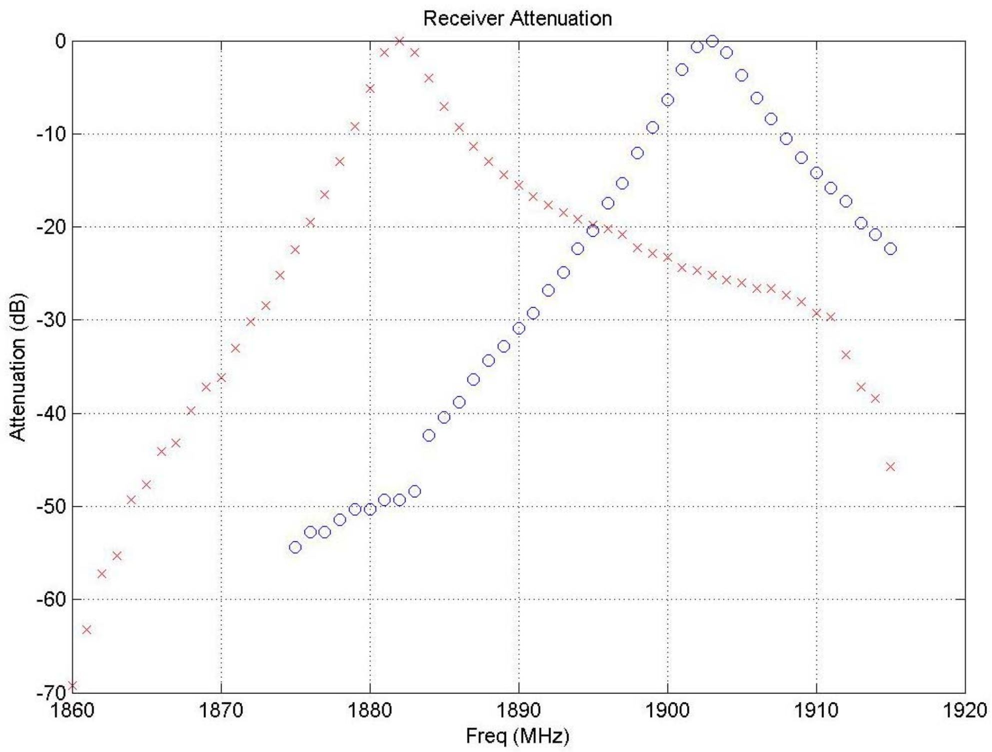


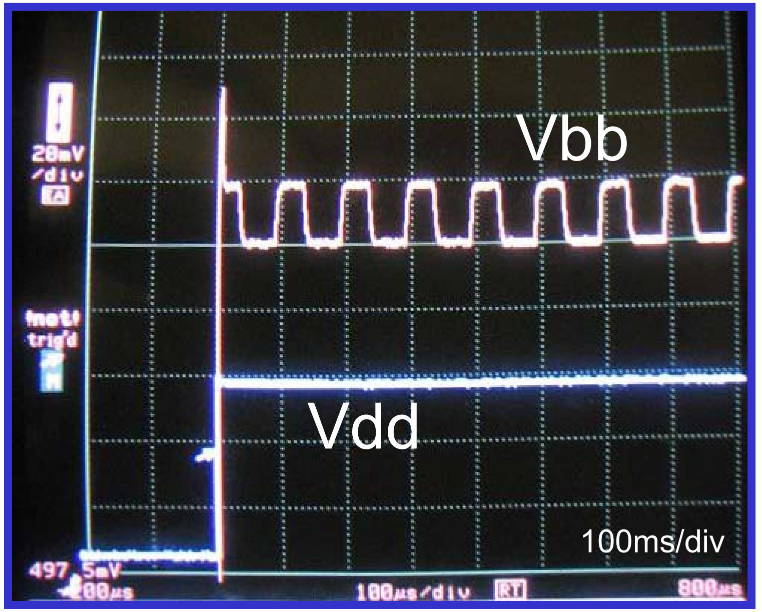


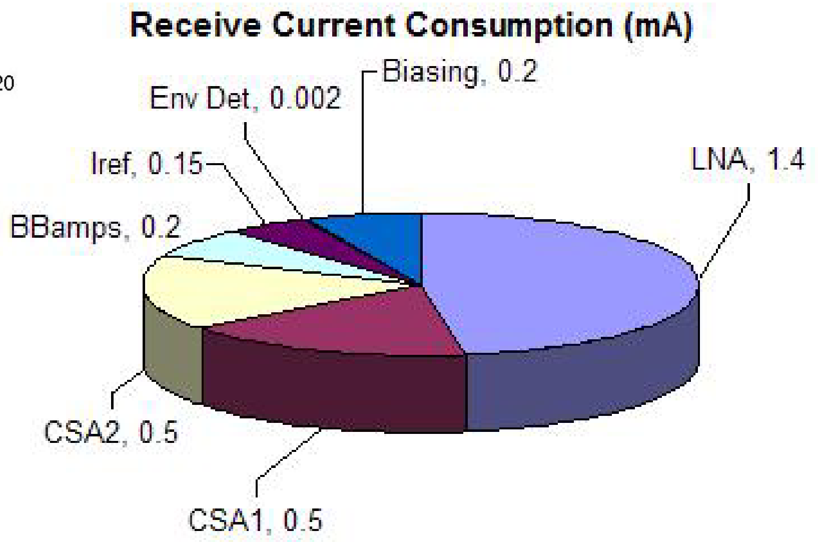
- Reliable transmission over 10m over hours of operation
- Battery operated



Receiver Results

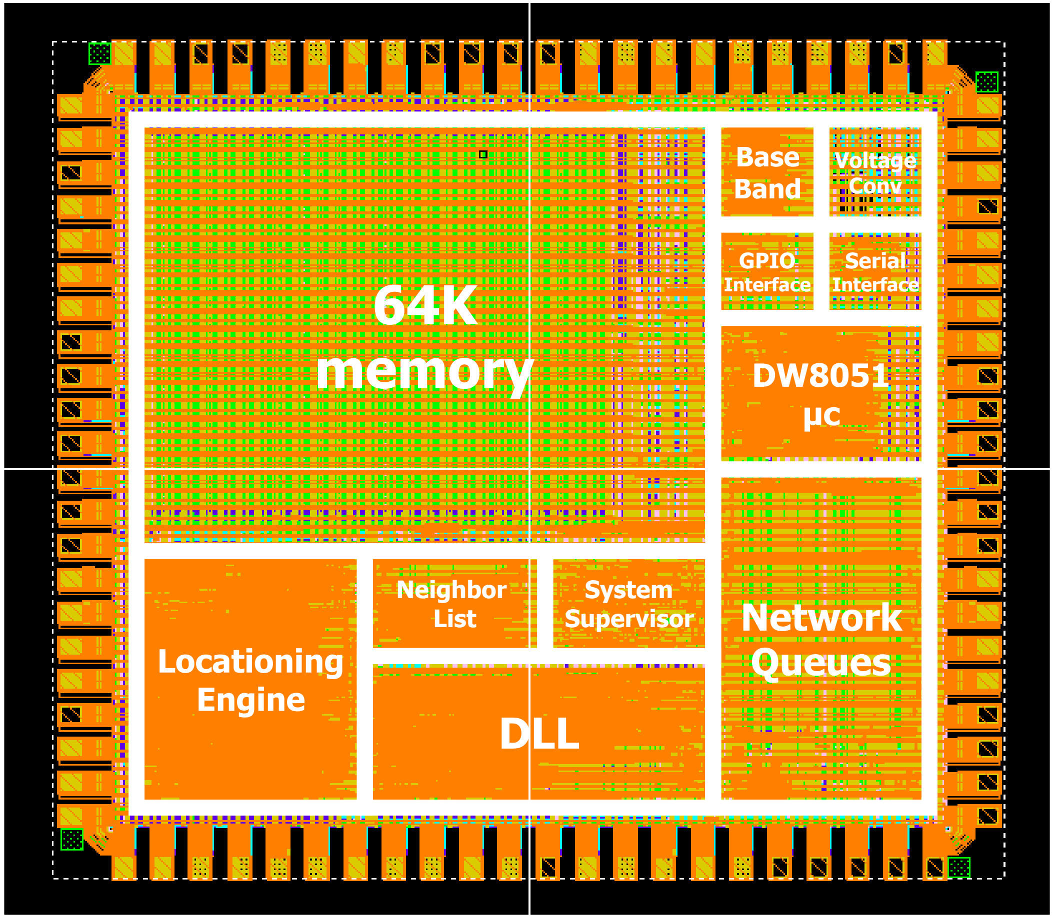






- -78dBm sensitivity (12dB SNR)
- 10μs turn-on time
- 3mA @ 1.2V supply

Wireless Sensor Network Protocol Processor



Technology	0.13µ CMOS
Chip Size	3mm x 2.75mm = 8.2 mm^2
Transistor Count	3.2M
Gate Count	62.5K gates
Clocks Freqs	16MHz(Main), 1MHz(BB)
On Chip memory	68Kbytes
Core Supply Voltages	1V(High) –0.3V(Low)
Pad Supply Voltage	1.8V
On_Power	< 1 mW
Pad Count	88

In fab (Jan 04)

Integrates all digital protocol and applications functions of wireless sensor node

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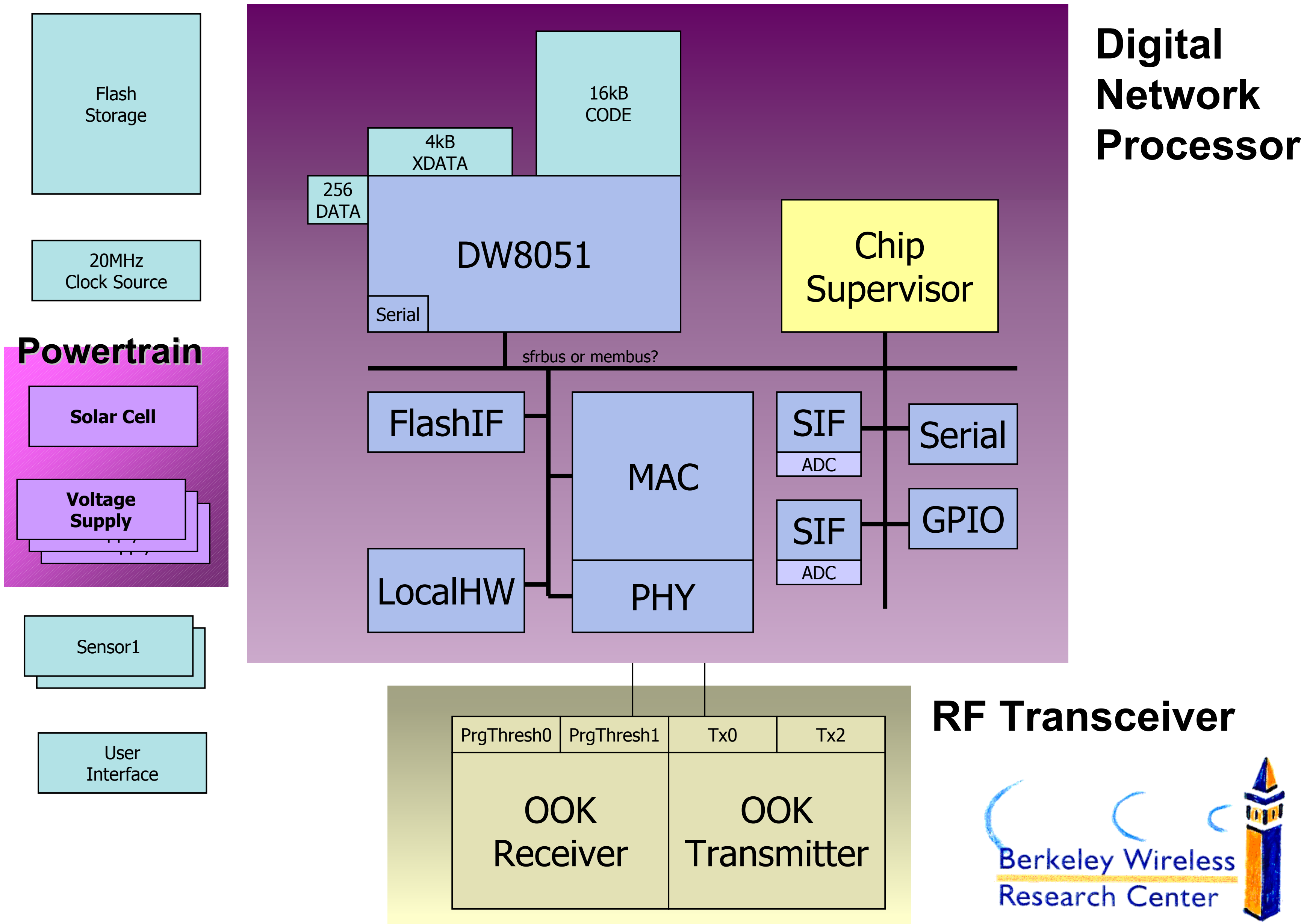
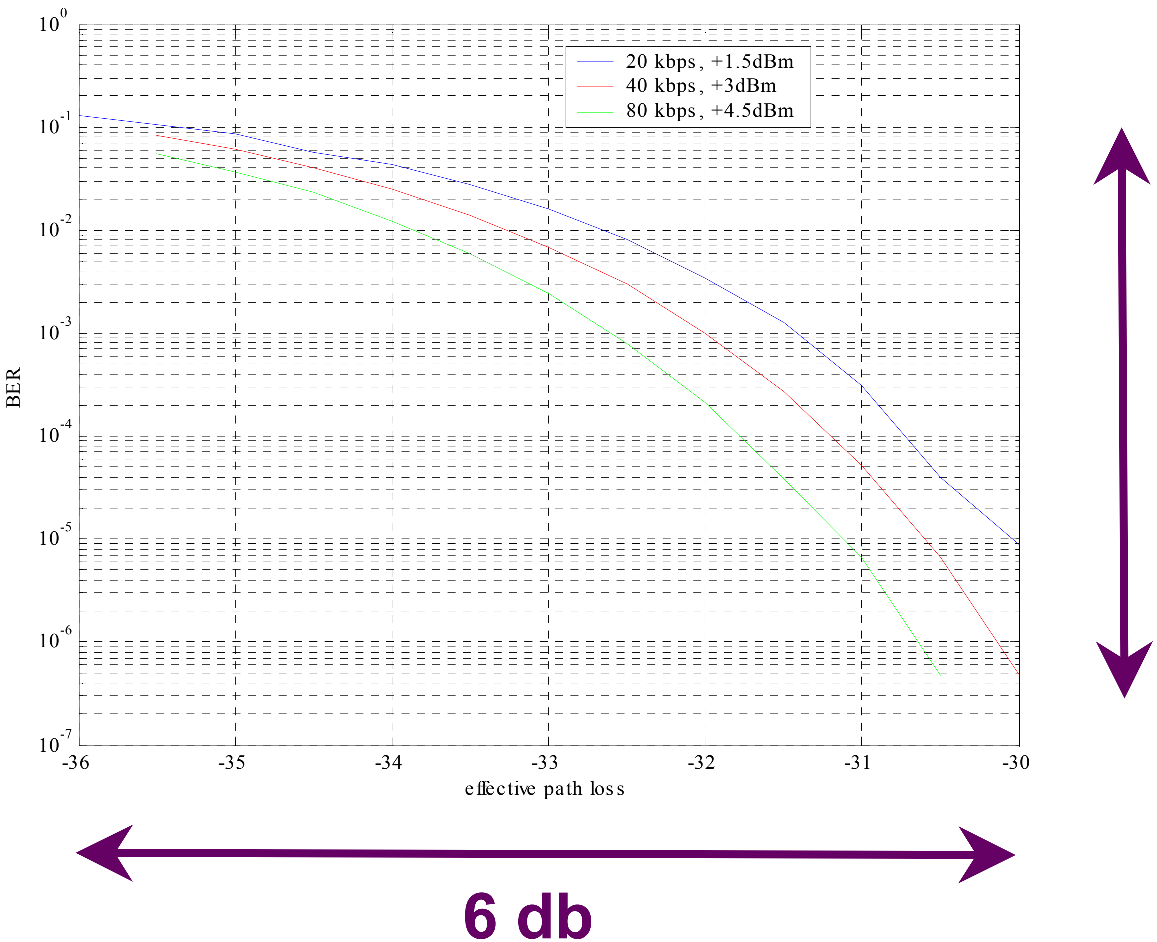
PicoNode: The first sub-milliwatt sensor node



Pro's or Con's of Simple Radio's



Small Change in Path Loss Has Dramatic Impact on Transmission Quality

– Channel is either "good" or "bad"

Simulated response of PicoNode radio

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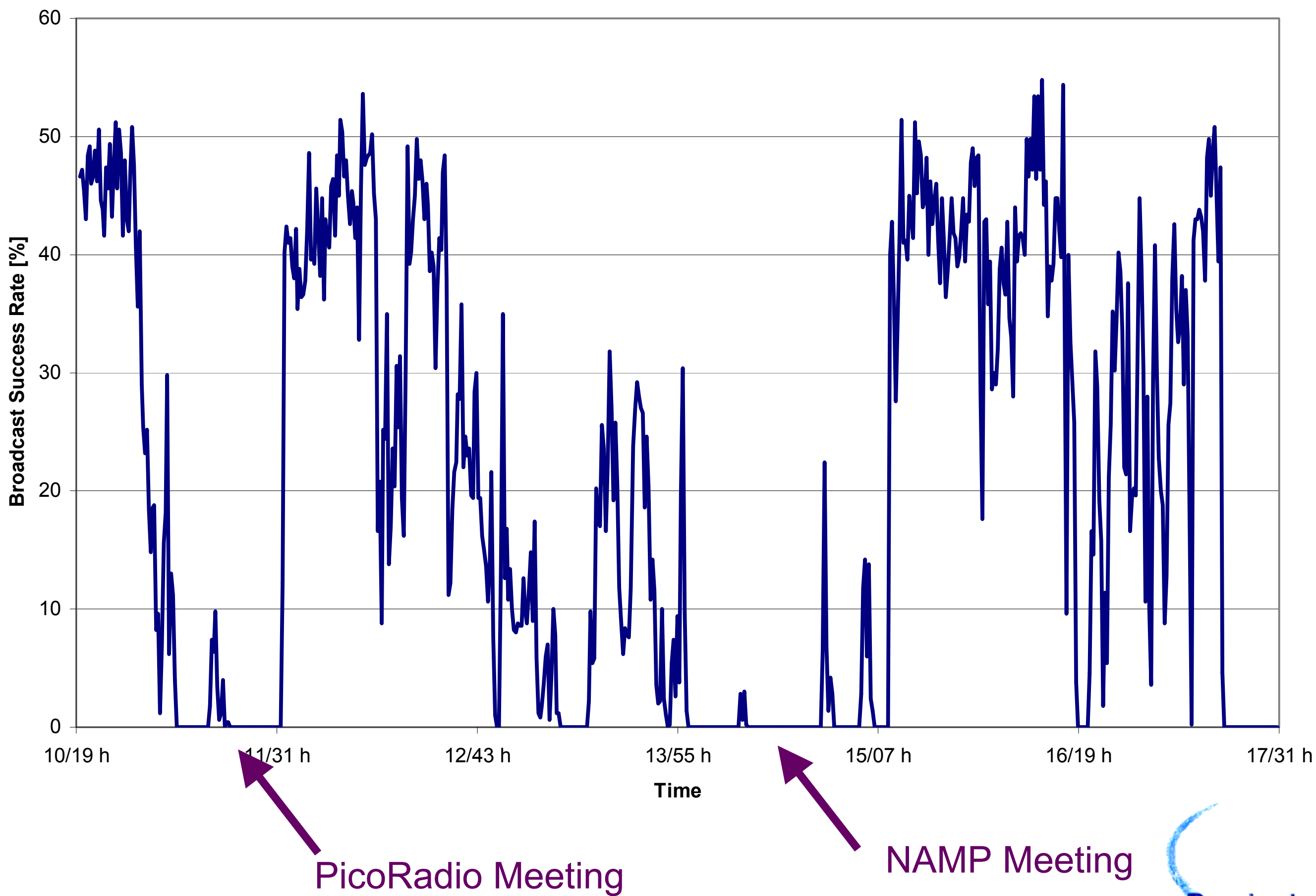
The Variability of Link Quality

Broadcast quality over time as measured at the BWRC round-table on a Friday



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Providing Robustness

- **Traditional radio's provide robustness through diversity:**
  - Frequency: e.g. wide-band solutions (hopping)
  - Time: e.g. spreading
  - Spatial: e.g. multiple antenna's
- **All these approaches either come with complexity, synchronization, or acquisition overhead, or might not even be applicable**
  - Data traffic irregular, and in very short bursts
- **A better approach: utilize the system properties!**

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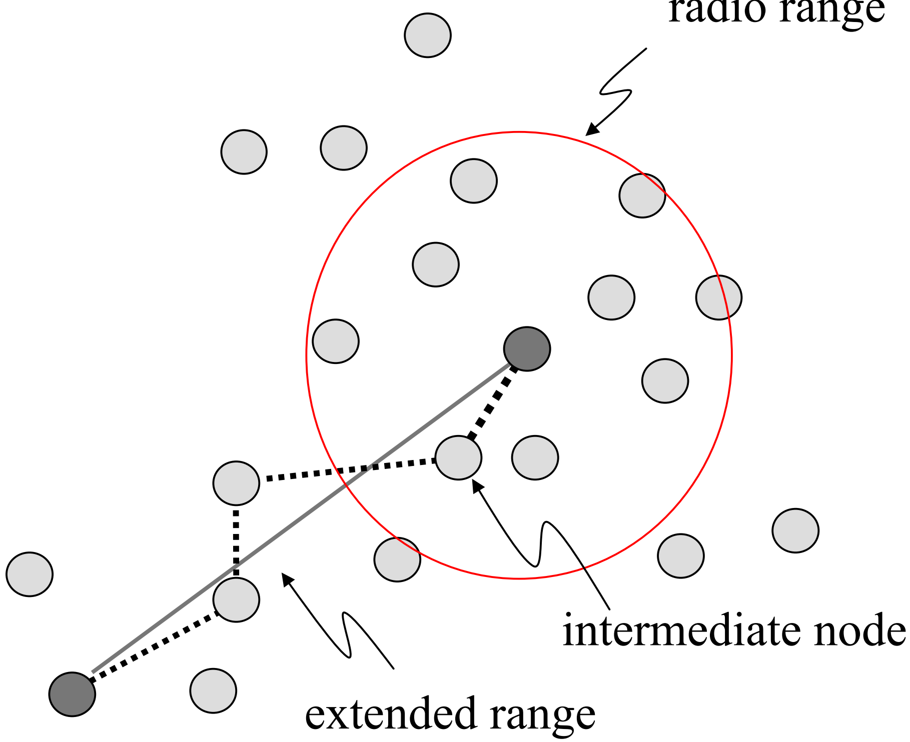
Ad-hoc Multi-Hop Networks

Use redundancy of wireless transceiver nodes to limit Tx power of individual radio to 0 dBm (~10 m)



@ 2.4 GHz assuming d^4 path loss

- 1 hop over 50 m: 10 nJ/bit
- 5 hops of 10 m each:
  5×16 pJ/bit = 80 pJ/bit

Multi-hop **reduces transmission energy by 125!**

In addition:
Multi-hop ad-hoc provides reliability and robustness

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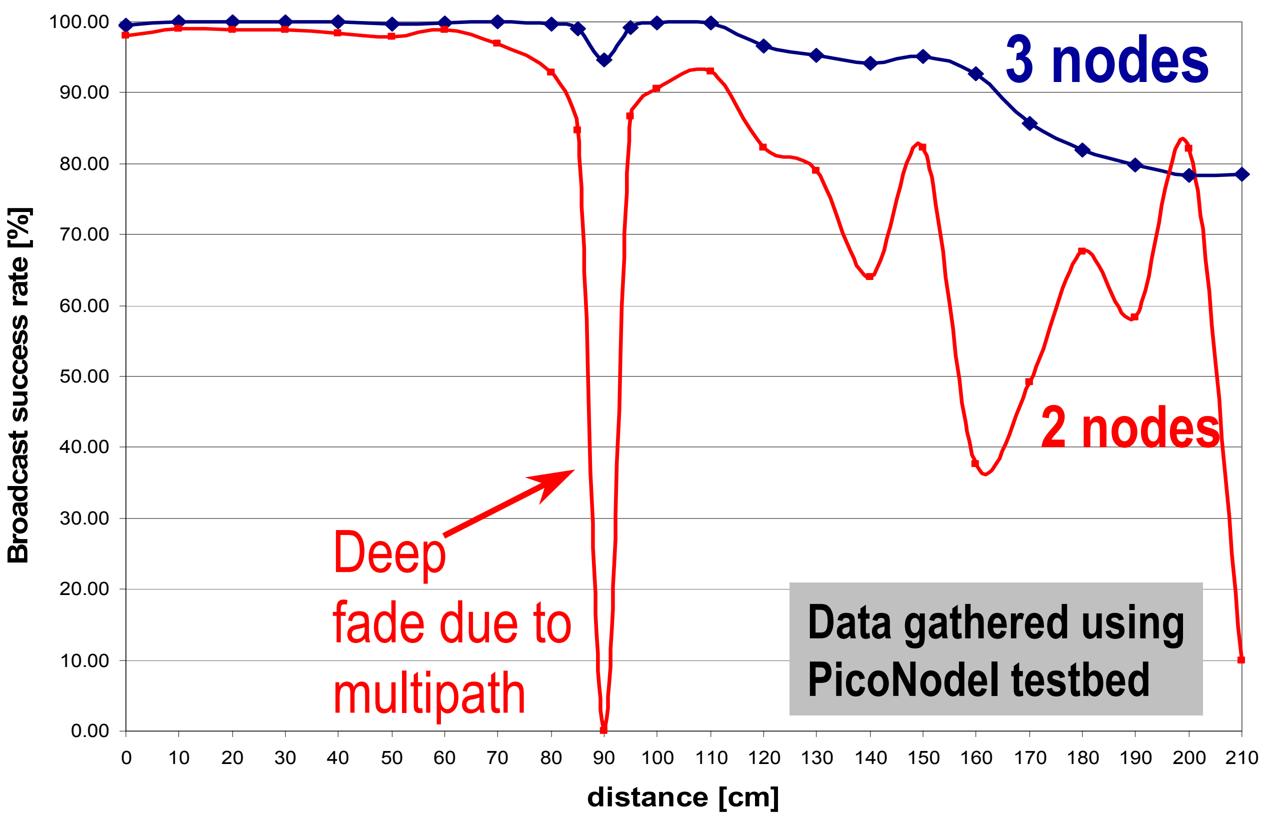
The Impact of Spatial Diversity



Adding a single node already changes broadcast reliability dramatically – spatial diversity is the preferred way to provide robustness in sensor networks

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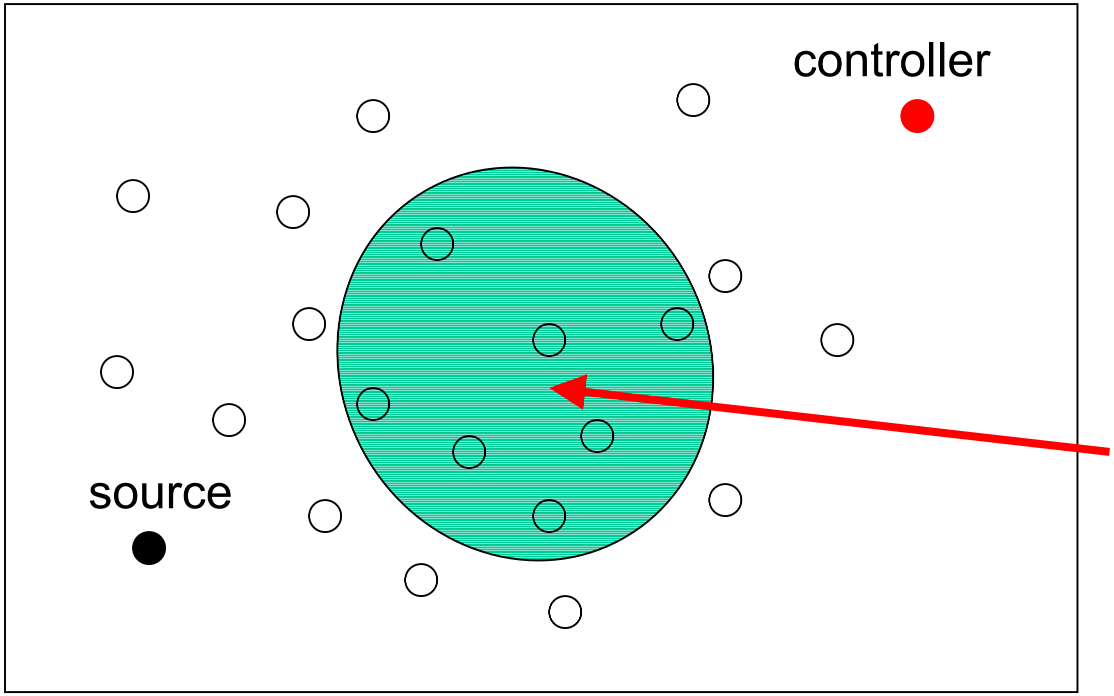
Exploiting density: EQUIVALENCE

Geographical routing

Forward packet to the first available node in an adjacent block closer to the destination



Nodes know:

- **Their own location**
- **The destination's location**

For routing purposes these nodes are equivalent

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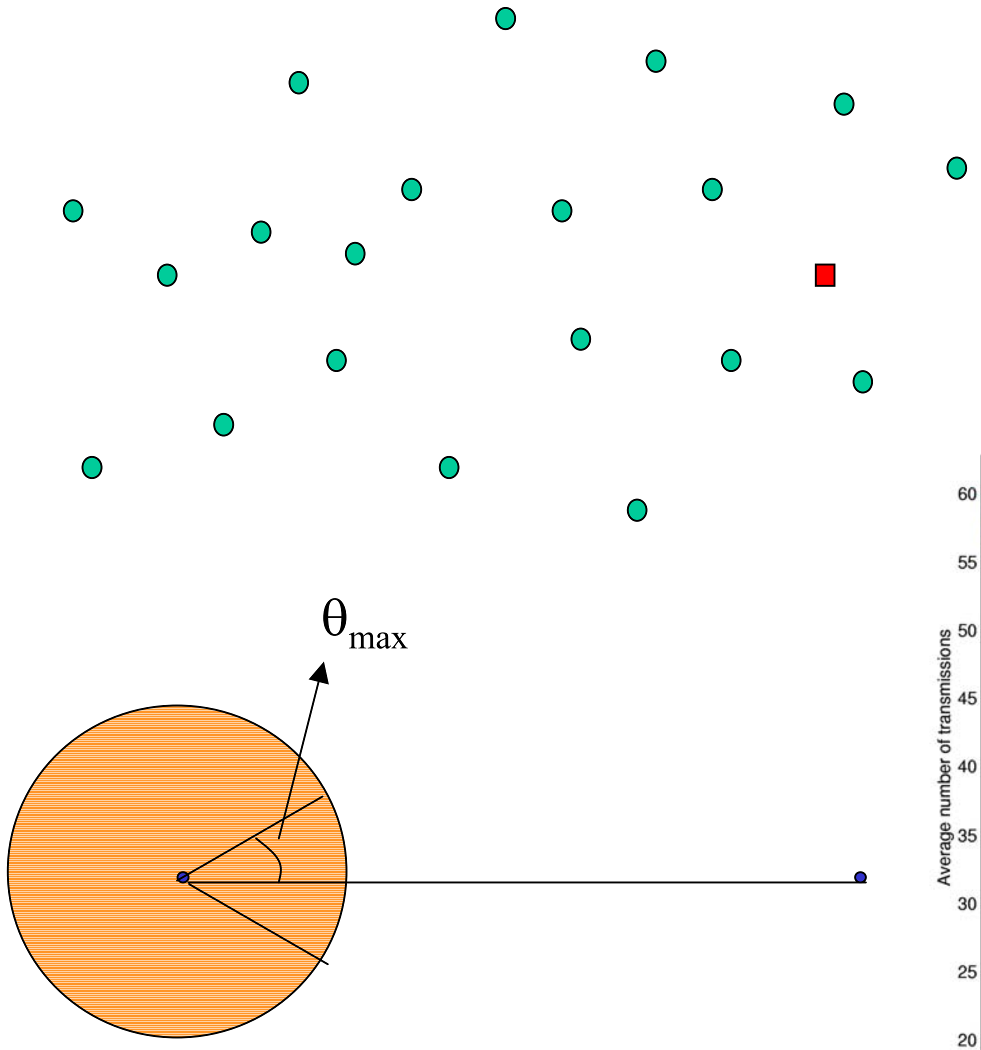
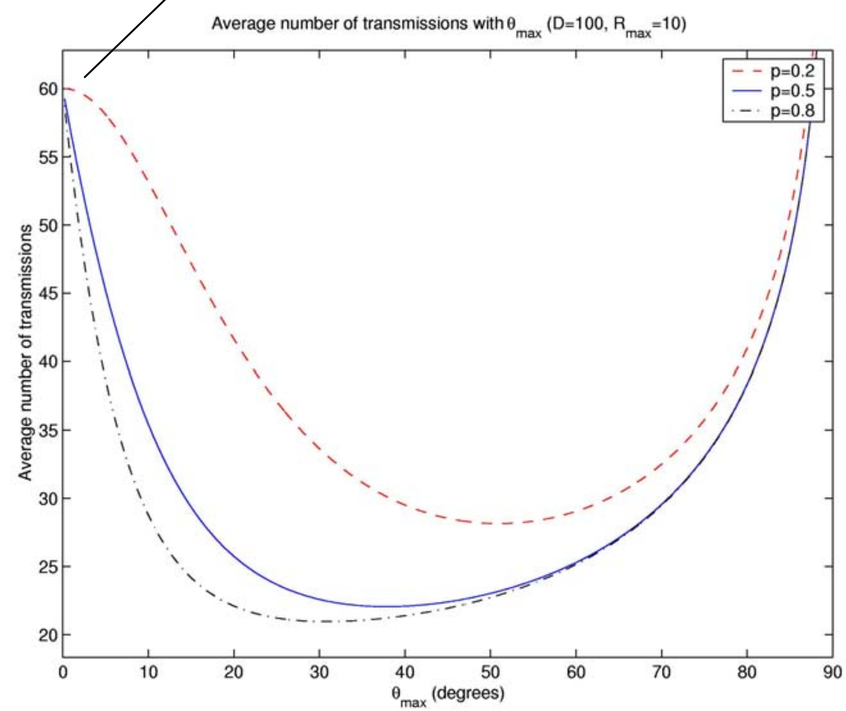
Routing exploiting spatial diversity



Limited by max number of retransmissions (3); packet is not delivered!



Going One Step Further: Embracing Randomness

- **Inherent Randomness**
  - Channels are unreliable
    - Changing multipath environment
    - Short time constants
  - Nodes are unreliable
    - May move
    - New nodes
    - May run out of energy
- **Added Randomness**
  - Nodes are duty cycled to preserve energy

Randomized Routing
Randomized Sleep Discipline

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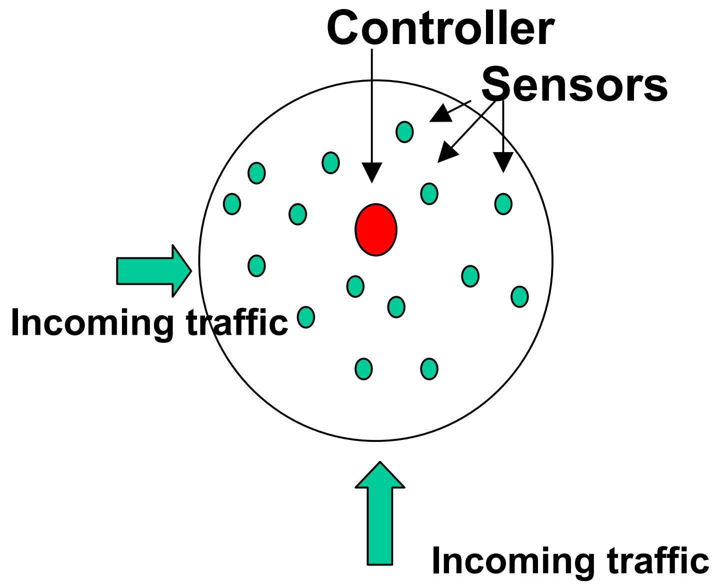
Randomized Sleep Discipline

SLEEP IF YOU CAN

- **Maintain connectivity**
- **If the node is not necessary, goes to sleep and saves power**



For how long should the node be allowed to sleep ?

Given:

1. Loss rate
2. Delay constraint
3. Data generation requirement

Our Solution

- Adaptive
  - Traffic & node density
- Random
  - Exponentially distributed sleeping times.
  - Avoid phase synchronization.

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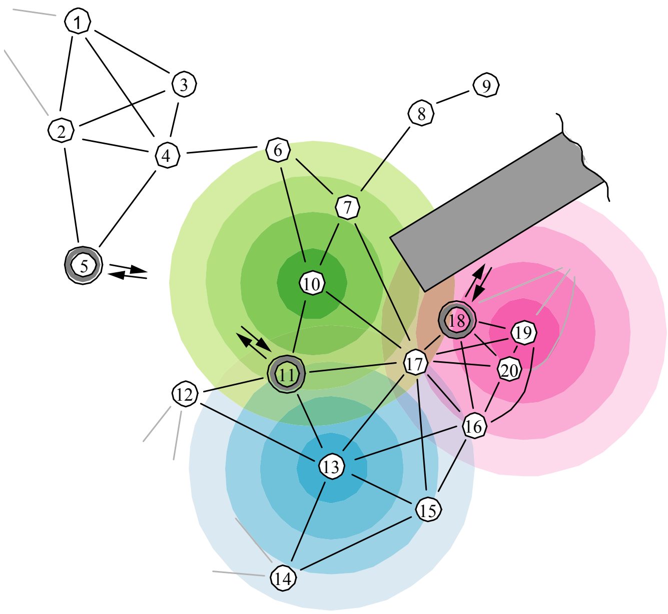
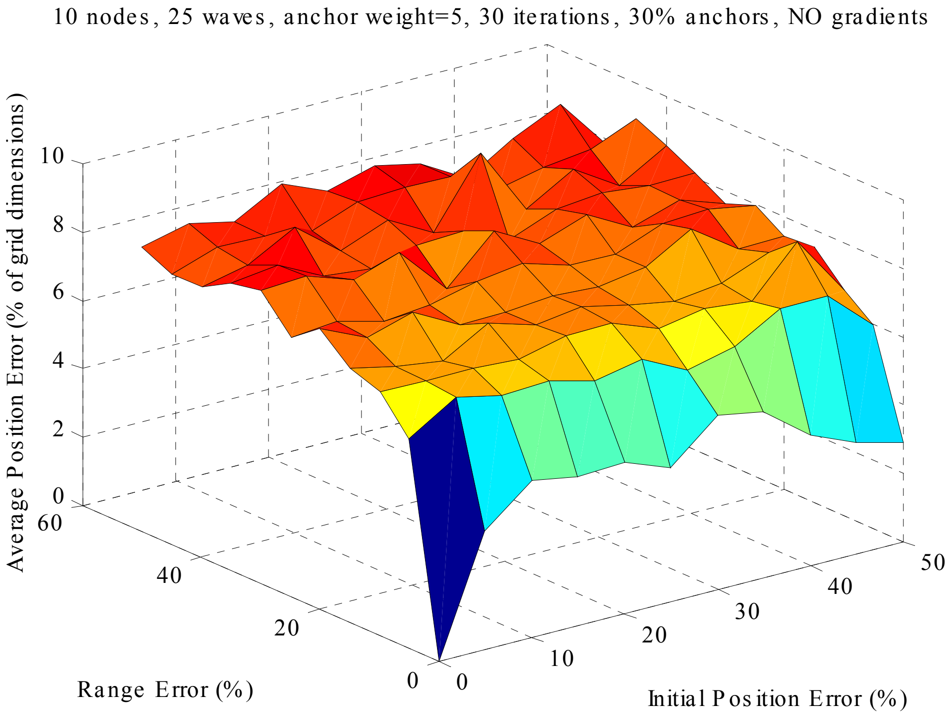
Distributed Positioning





– Location information helps to reduce networking overhead
– Connectivity of Pico Networks enables distributed locationing, integrated into media access layer

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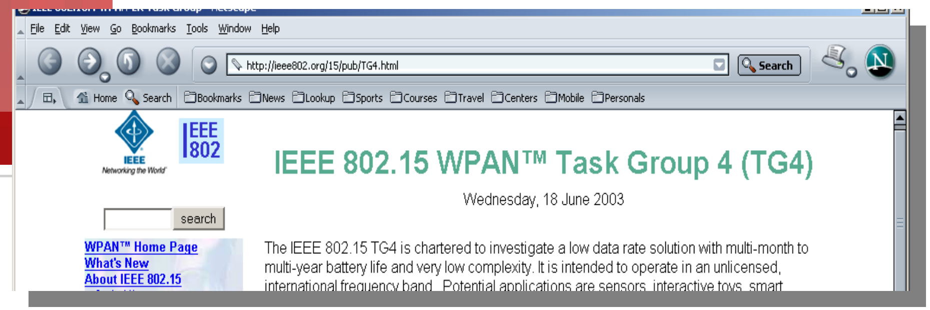
A Quest: An Application Perspective to Sensor Networks

A plethora of implementation strategies emerging, some of them being translated into standards



TinyOs/TinyDB

The juggernaut is rolling … but is it the right approach?

- Bottom-up definition without perspective on interoperability and portability
- Little reflection on how this translates into applications

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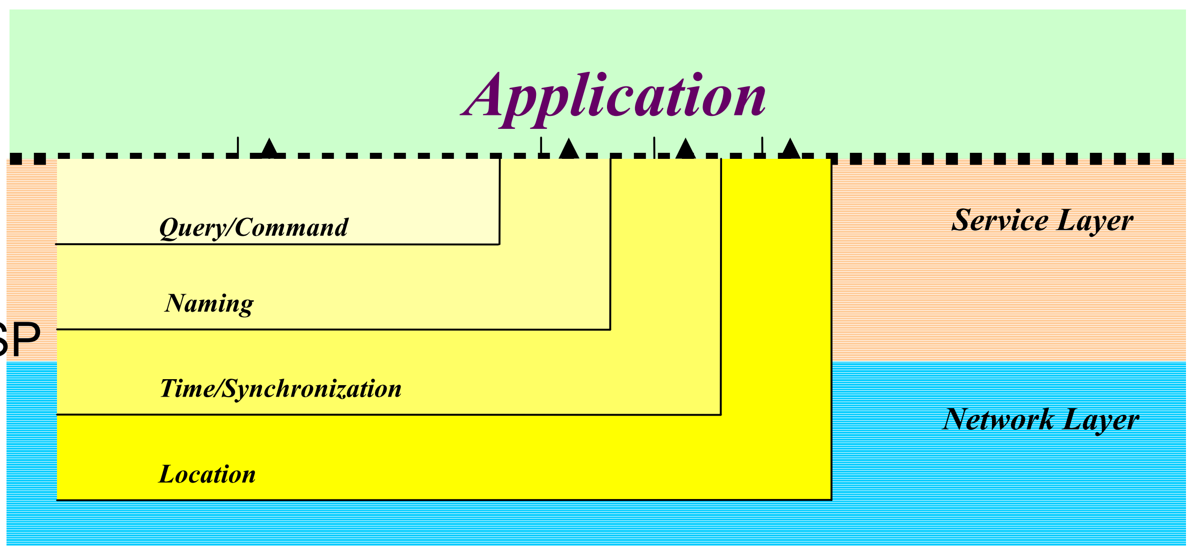
An Alternative Approach: A Universal Application Interface (AI)

- **Supports essential services such as queries, commands, time synchronization, localization, and concepts repository**
- **Similar in concept to the socket interface in the internet**
- **Provides a single point for providing interoperability**
- **Independent of implementation architecture and hardware platform**
  - Allows for alternative PHY, MAC, and Network approaches and keeps the door open for innovation

SNSP



Application Interface

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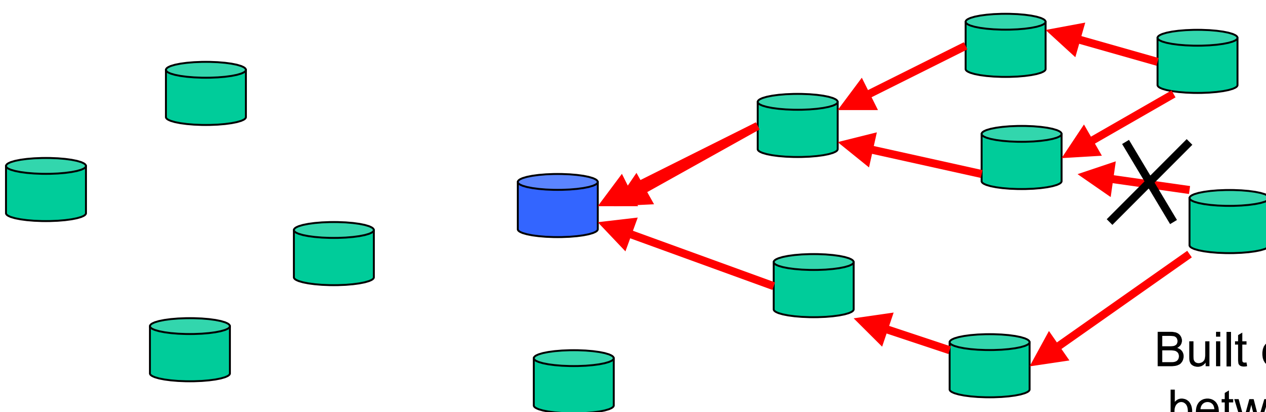
Providing essential services in an energy-efficient way

- Meaningful operation of sensor network requires that nodes are aware of some essential parameters (position, time, network and hardware resources)
- Main challenge is how to make this available in a distributed environment in a reliable and energy-efficient way

Example: distributed light-weight time synchronization (using spanning trees)



Built on pair-wise synchronization between nodes

For 50 ppm clock
30 synchronization events per node/10 hours yields 0.5 sec. accuracy

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SNSP Status (joint project with TU Berlin)

- **White paper completed and in feedback gathering mode (http://bwrc.eecs.berkeley.edu/research/picoradio/...)**
- **Very positive support so far (both from industry, government, and academia)**
- **Next targets:**
  - Further evolve document (start working group)
  - Demonstrate feasibility by implementation on at least two test beds
  - Address number of issues left open for research (e.g. implementation approaches for naming, synchronization, localization, and concept repository services)

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Summary And Perspectives

- **Ambient Intelligence and low data rate sensor networks rapidly emerging as a major new player in the information technopogy arena**
  - Opening the door for a whole new set of exciting opportunities
  - Leading to TRULY embedded electronics
- **Bringing new meaning to the word "low-power" and "cool chips"**
- **Require a fresh look at wireless integrated system design!!!**
- **But … A number of intriguing challenges still to be overcome**

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