Ultra-low Power Computation and Communication enables Ambient Intelligence

Jan M. Rabaey

And the PicoRadio Group

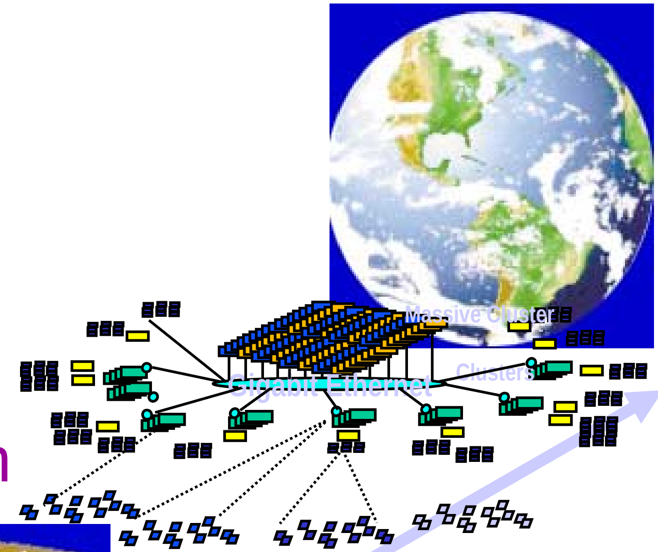
Berkeley Wireless Research Center

Department of EECS, University of California, Berkeley

http://bwrc.eecs.berkeley.edu

The New Internet—
Societal-Scale Systems

The 1990s:
Conquering the world
The network revolution



The 2000s:
Extending toward the small
Enabled by integration
and wireless connectivity

Pre-1990:
Client-Server systems

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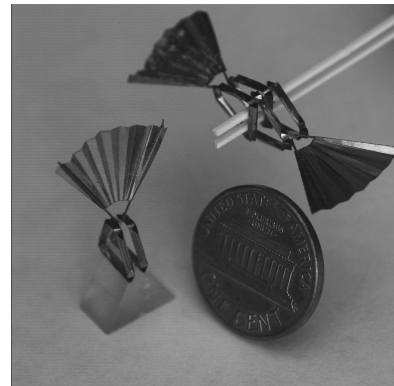
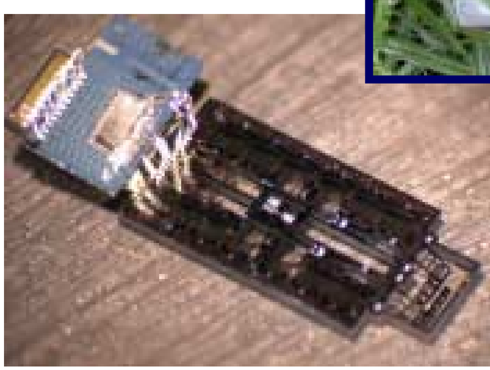
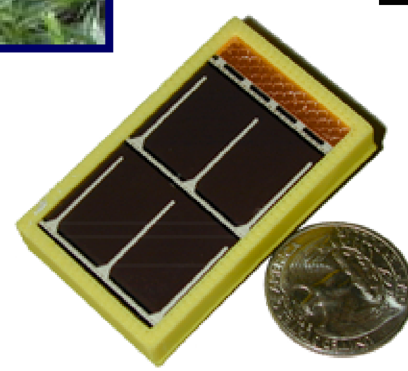
Towards Fully Integrated Embedded Systems-on-a-Chip or in-a-Package

While increased performance has been the hallmark result of Moore's law, miniaturization and cost reduction opens the door for truly ubiquitous electronics







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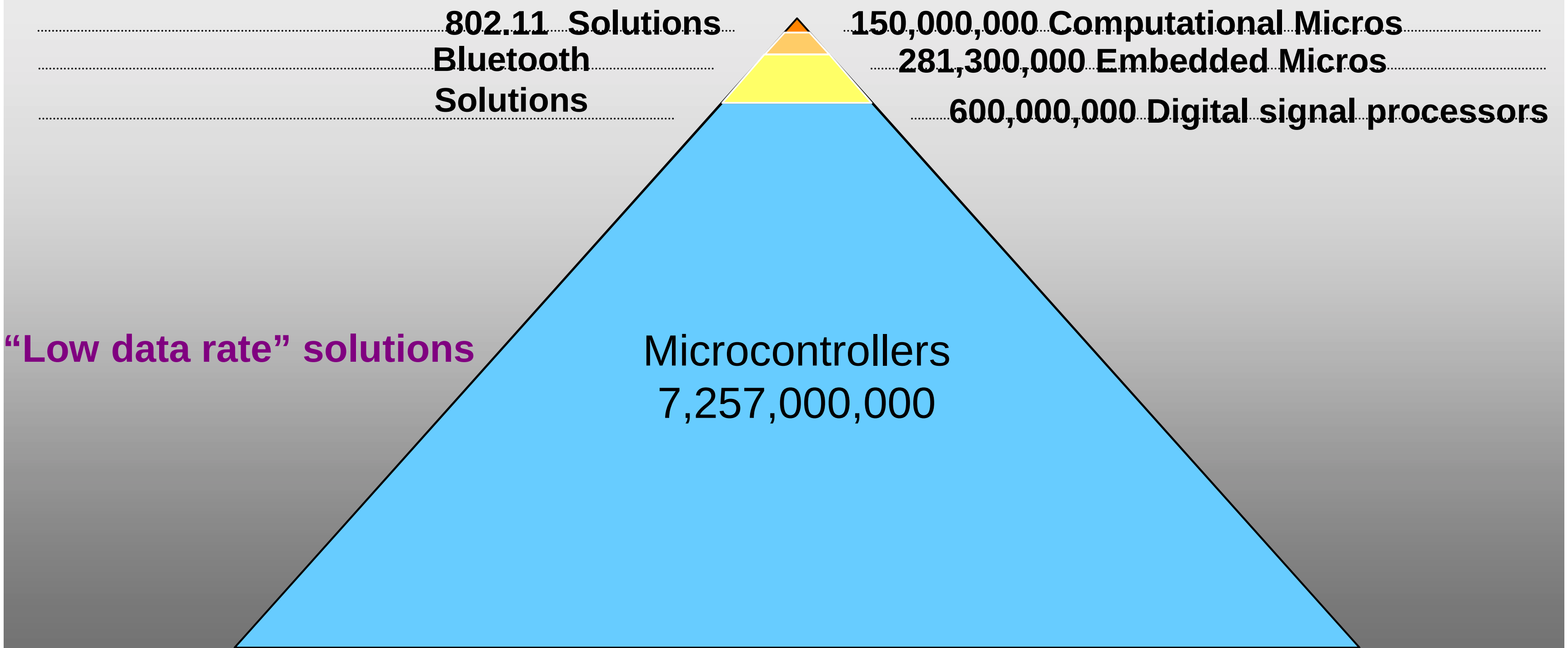
Creates a New Agenda In Wireless



Source: DARPA as reprinted in "Communications of the ACM"; May 2000/Vol. 43, No.5 (Courtesy Rob Poon, Ember Technologies)

Key Metrics:

Cost, Size, Power, Reliability, and Ease of Use

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ZigBee™ Alliance

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The ZigBee Alliance is an association of companies working together to create a very low-cost, very low power consumption, two-way, wireless communications standard. This wireless communications solution will be embedded in consumer electronics, home and building automation, industrial controls, PC peripherals, medical sensor applications, toys and games.

Andy Rappaport, August Capital

"I can see at most 5 or 6 applications for high data-rate wireless connectivity, while I see numerous ones for low-data rate ad-hoc",

BWRC Retreat, Jan. 2003

CMP United Business Media

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Companies test prototype wireless-sensor nets

By R. Colin Johnson
EE Times
January 29, 2003 (4:46 p.m. EST)

PRINT THIS STORY | SEND AS EMAIL

PORTLAND, Ore. — Self-organizing wireless-sensor networks, a realization of the Pentagon's "smart-dust" concept, have reached the prototype stage worldwide. The smart sensors, or Motes, were created by the University of California at Berkeley and Intel, and are being tested out worldwide today.

Recent Articles
EET
- Appeals court rules for Rambus in patent case
- Research expert ponders next killer application

"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

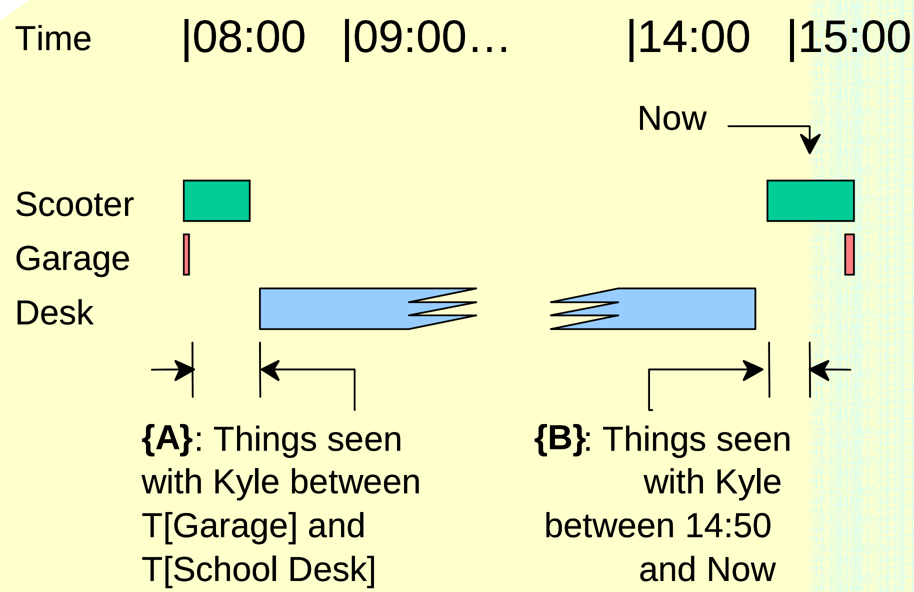
Fred Boekhorst, Philips, ISSCC02

An Example: Solving Everyday's Problems

Keeping track of Kyle's scooter

ID32	First seen	Last seen
Scooter	**08:02**	**08:26**
Garage	**08:02**	**08:04**
School Desk	**08:31**	**11:32**
School Desk	**12:32**	**14:45**
Scooter	**14:50**	**15:22**
Garage	**15:18**	**15:22**

HPlabs and BWRC



If {A} # {B} so Alert("Forgot Scooter")

Tackling Societal Scale Problems

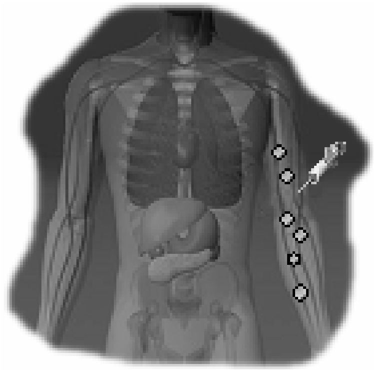
Disaster Mitigation

Smart buildings

Traffic management

Infrastructure maintenance

Energy management



Medical

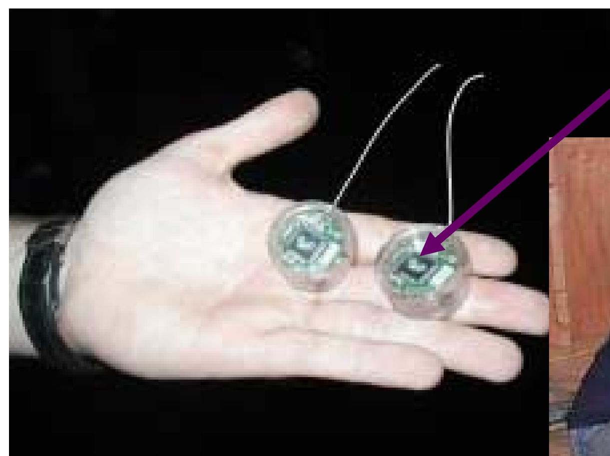
CITRIS
Center for Information Technology Research in the Interest of Society

Example: Seismic Monitoring of Buildings

BEFORE

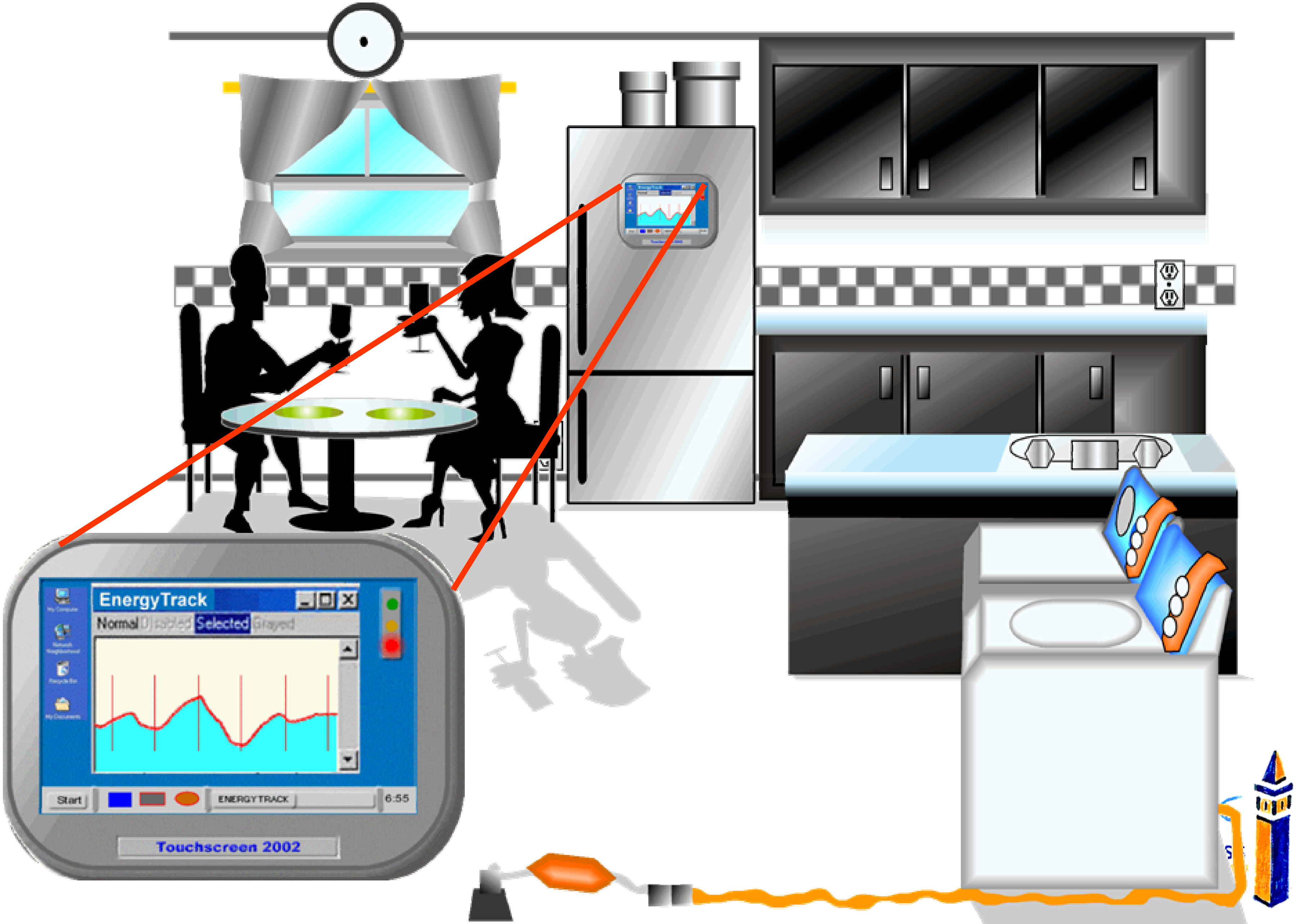
$8000 each

$70 each



AFTER

Energy-Aware Buildings

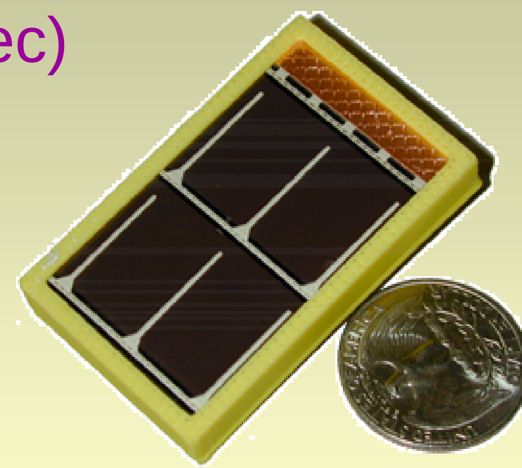


PicoRadio's

Ubiquitous Sensor and Monitor Networks

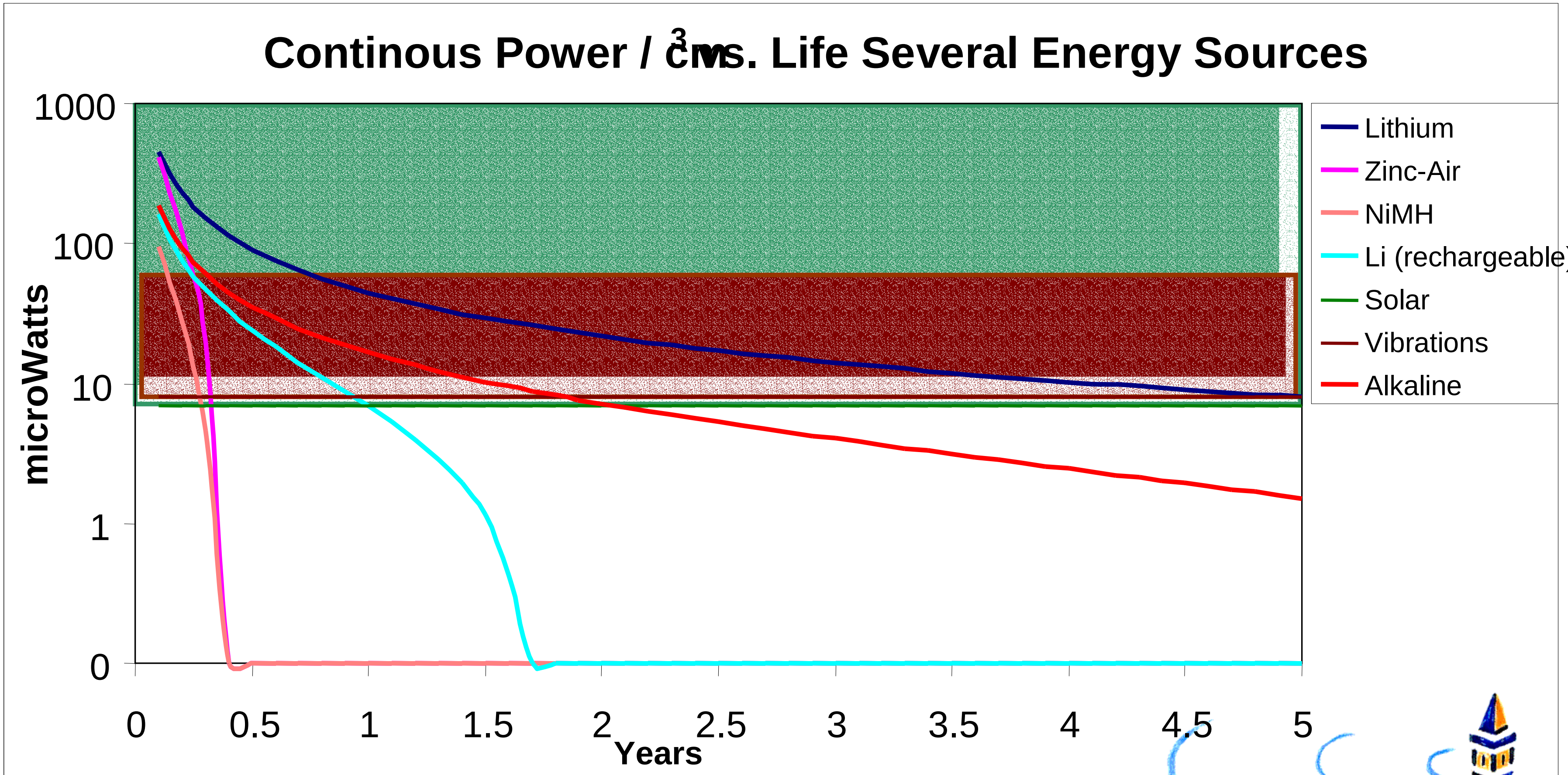
Meso-scale low-cost radio's for ubiquitous wireless data acquisition that

- support low data-rates (< 100 kBit/sec)
- are fully integrated
  - –Size smaller than 1 cm^3
- minimize power/energy dissipation
  - – Limiting power dissipation to 100 μW enables energy scavenging
- and form self-configuring, robust, ad-hoc networks containing 100's to 1000's of nodes



Energy Scavenging

How much energy can be obtained from a volume of 1 cm^3?



Source: S. Roundy (UCB)

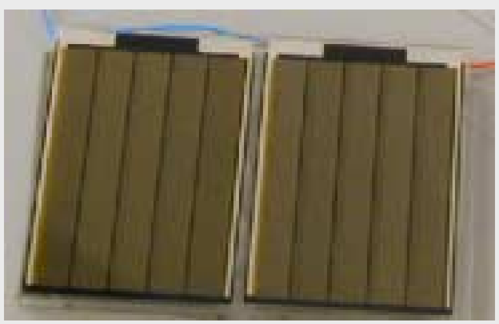
Practical Means of Energy Scavenging

Piezoelectric bi-morphs

PZT

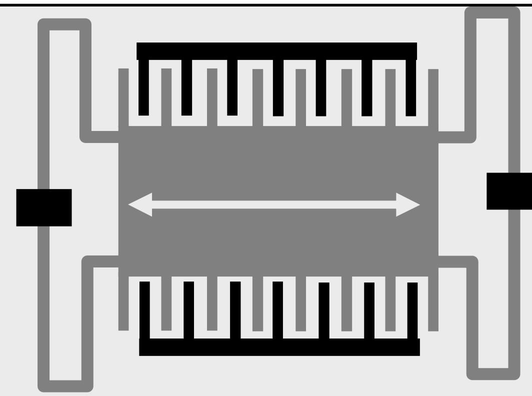
90 μW/cm³

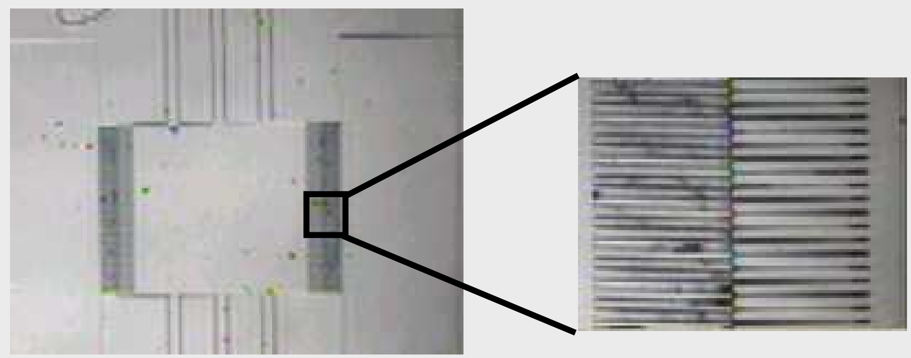
PVDF



Photovoltaic

10-1500 μW/cm²

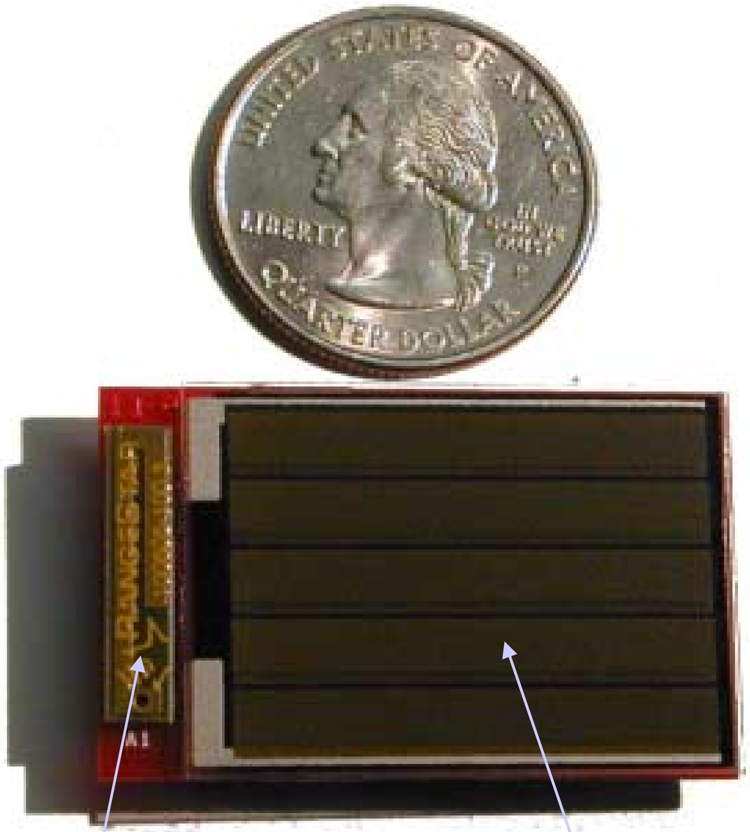


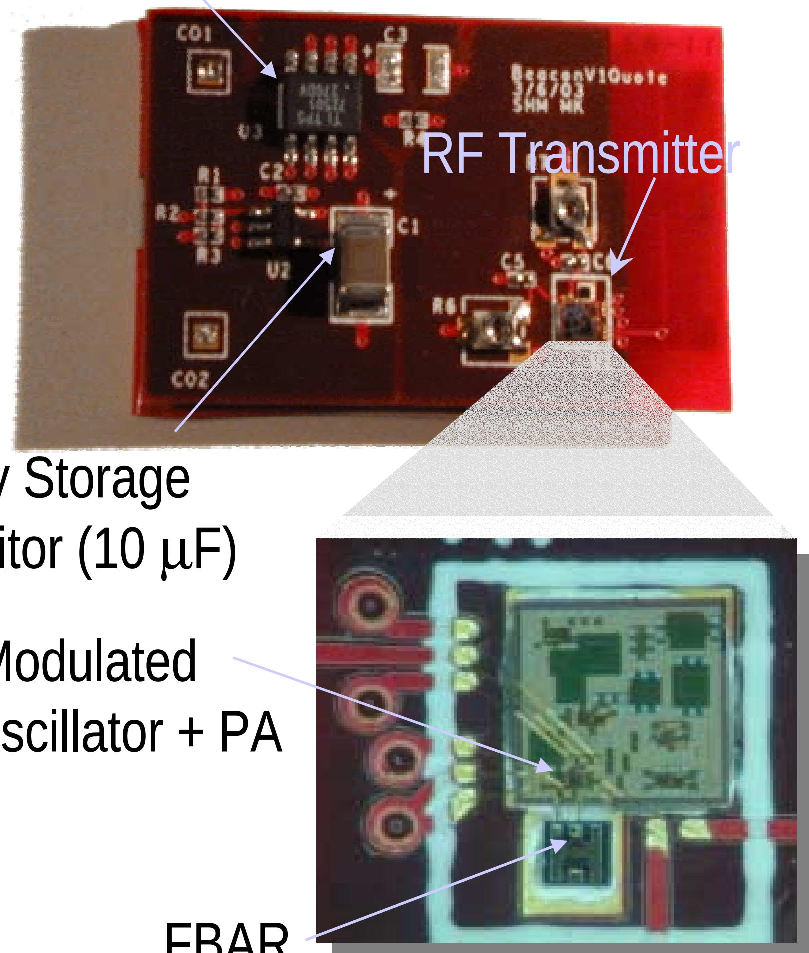


Capacitive converter using
MEMS micro-vibrator
30 μW/cm³ (on microwave oven)

[Shad Roundy (IML,UCB)]

PicoBeacon: An Energy-Scavenging Radio





An exercise in miniaturization and energy scavenging

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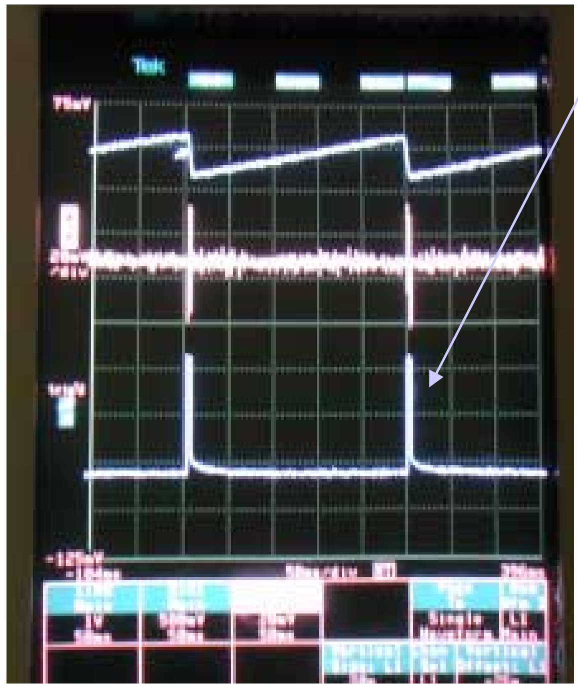
PicoBeacon: An Energy-Scavenging Radio

Voltage over capacitor

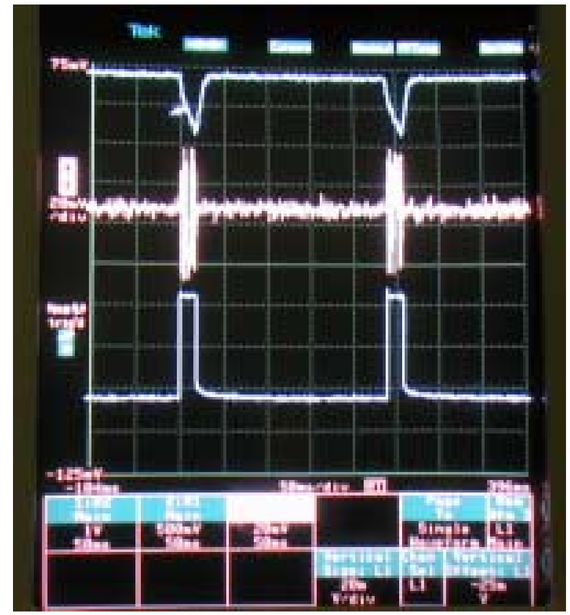
Observed RF signal

Radio duty-cycle

Ambient light



Medium light



Intense light †

† Duty cycle upper-bounded by latency of comparator

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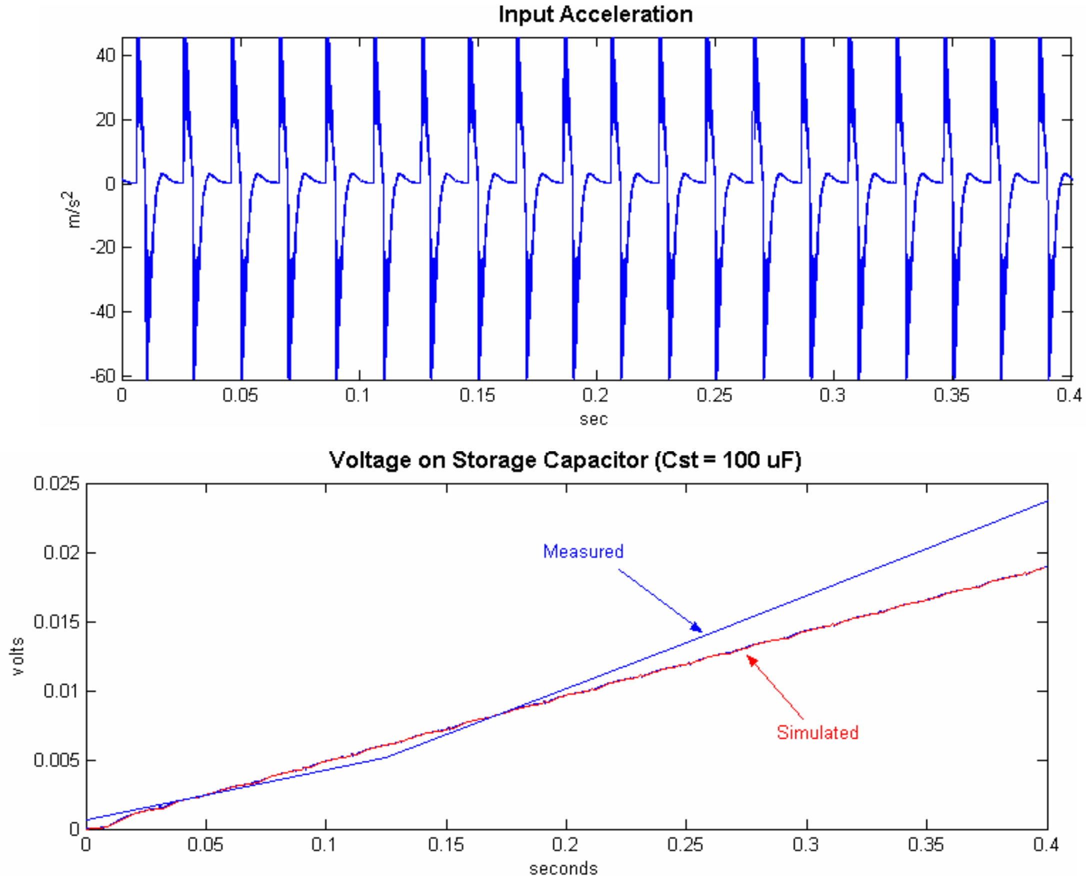
Energy Scavenging - Vibration



Piezo-bender prototyped for "in-tire" sensor network

Other options: Thermo-electric, electromagnetic, fuel cells, microengines (ISSCC 03)

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Getting energy from temperature difference

Using heat of a hand

Using cold water

Bi-Te based thermoelectric converter

Battery-less wireless signal transmission using temperature difference

The road to low-energy, low-cost, small-size solutions

- **Simplicity rules!**
  - Advanced techniques used in traditional wireless links are not necessarily relevant
- **Standby power the greatest enemy**
  - Monitoring connectivity dominates overall power
  - Leakage dominates digital power
- **Redundancy as a means to create robustness**
  - Elements and links can and will fail
  - Learning about the environment may not be worthwhile if it changes rapidly

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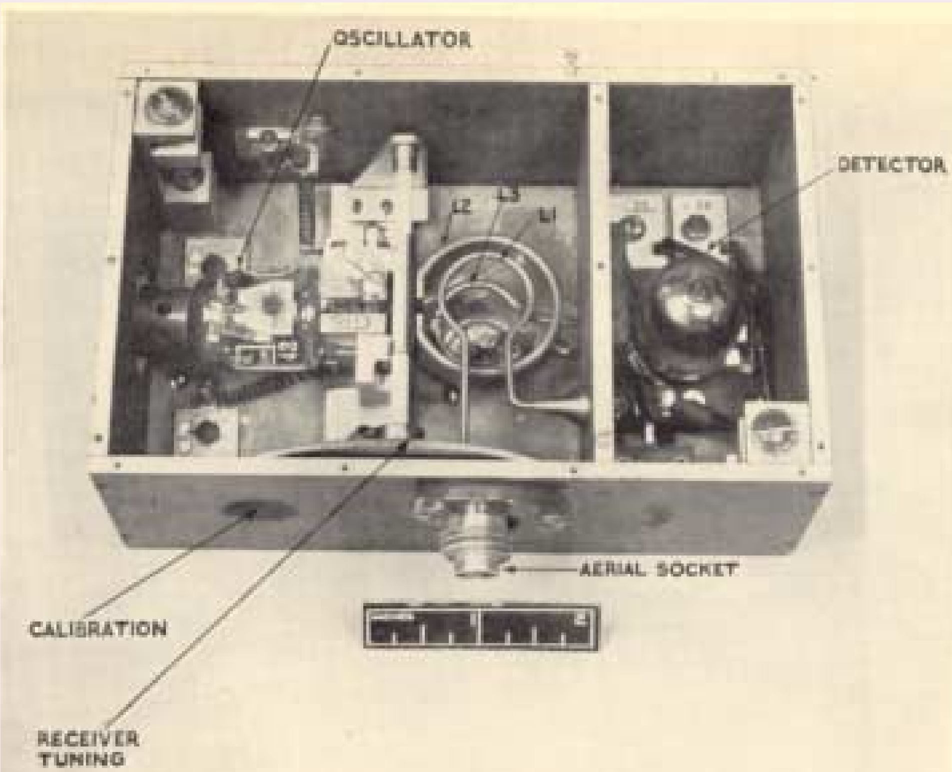
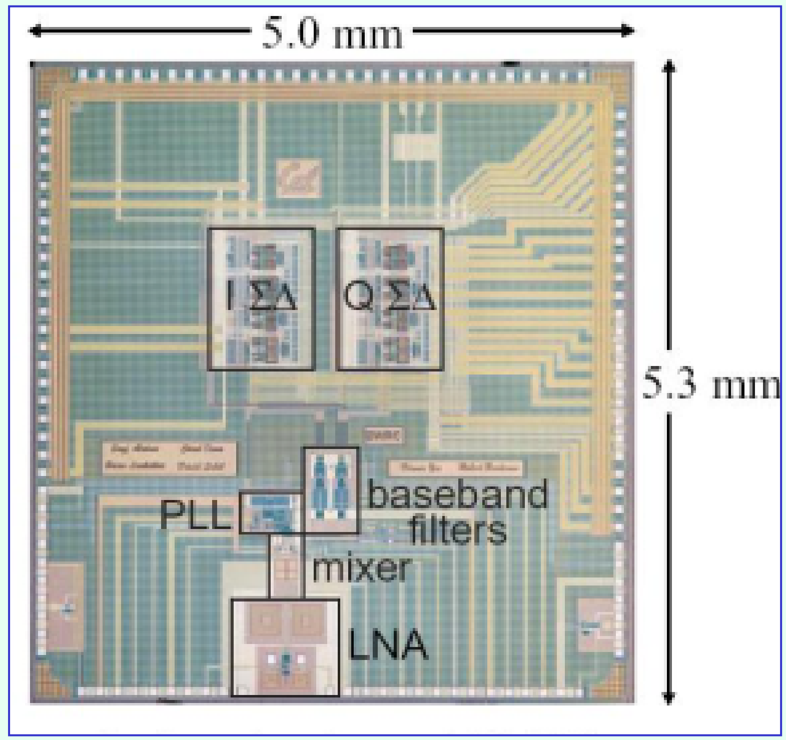
Low-Power RF: Back to The Future

(Courtesy of Brian Otis)



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

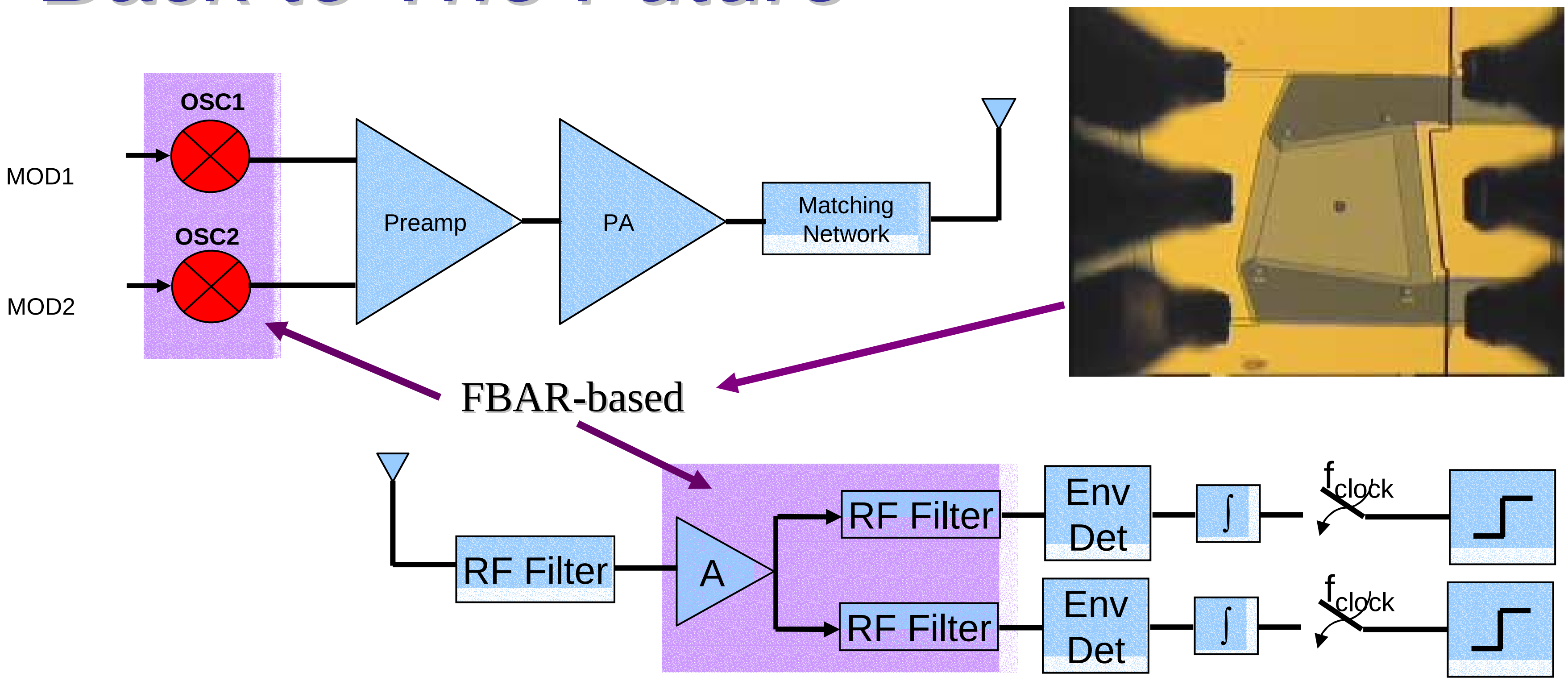
© 2000 - Direct Conversion
f_c= 2GHz
>10000 active devices
no off-chip components



D. Yee, UCB

Back to The Future

Thin-Film Bulk Acoustic Resonator

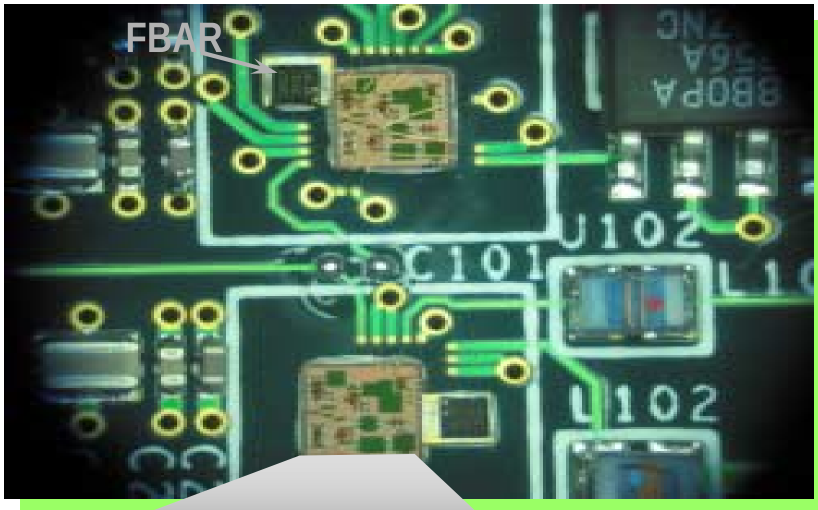


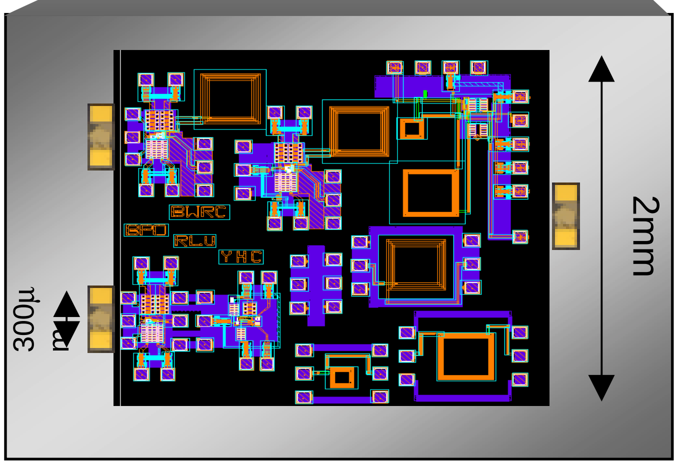
Simplicity Rules

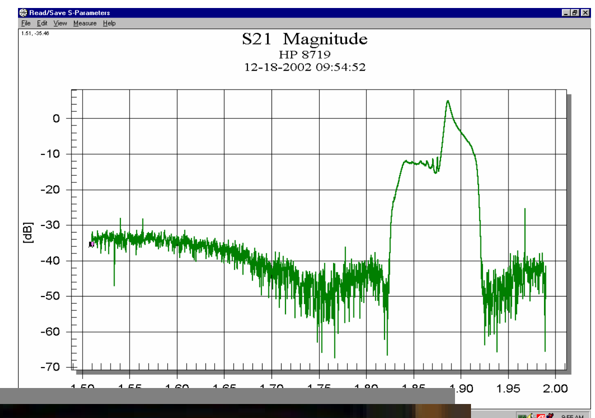
- Minimizes use of active components – **exploits new technologies**
- Uses simple modulation scheme (OOK)
- Allows efficient non-linear PA
- Down-conversion through non-linearity (Envelope Detector)
- **Tx and Rx in 3-4 mW range** (when on)

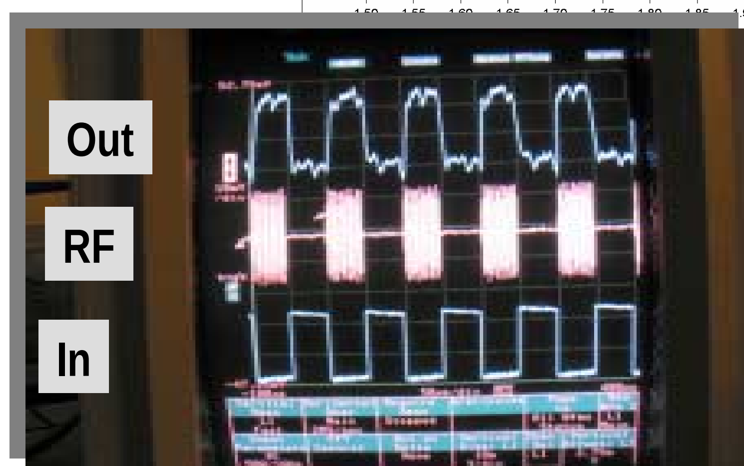
An Operational PicoRadio (RF)

Single channel 4 mW transceiver
(assembled from prototype components)
Overall silicon area: a couple of mm^2!

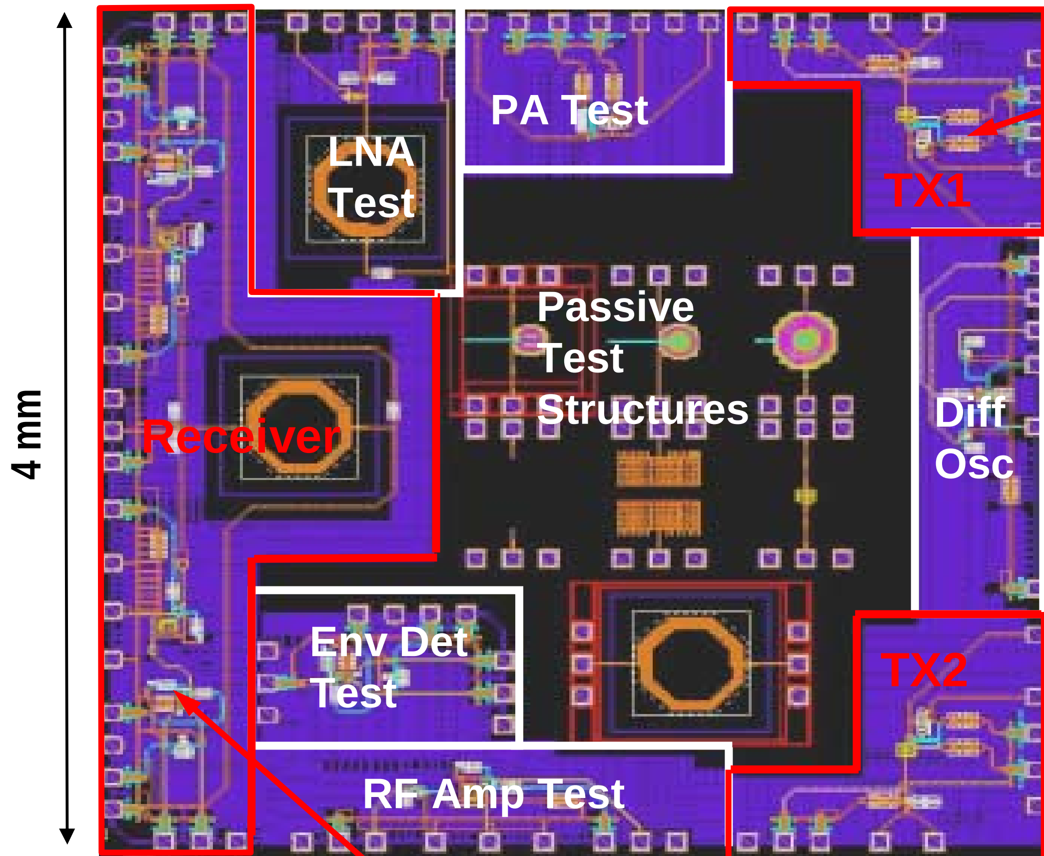


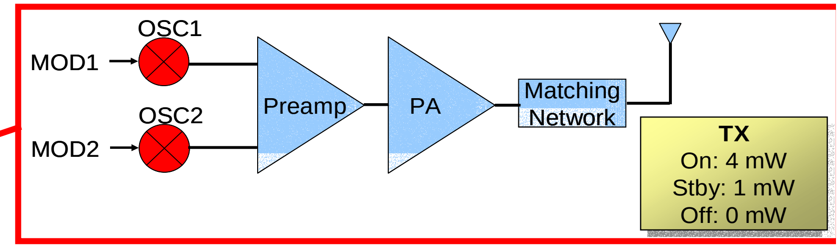




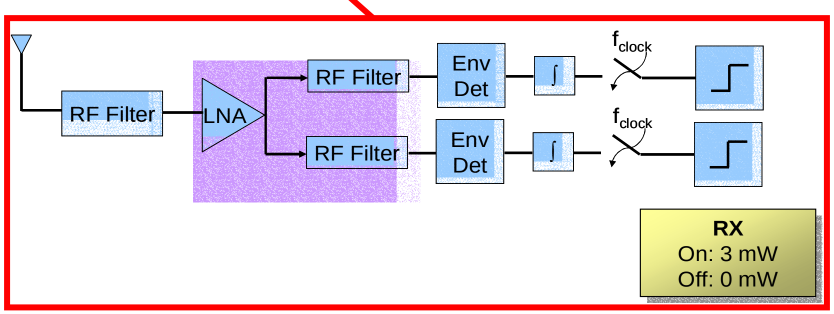


The Integrated Version





- 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



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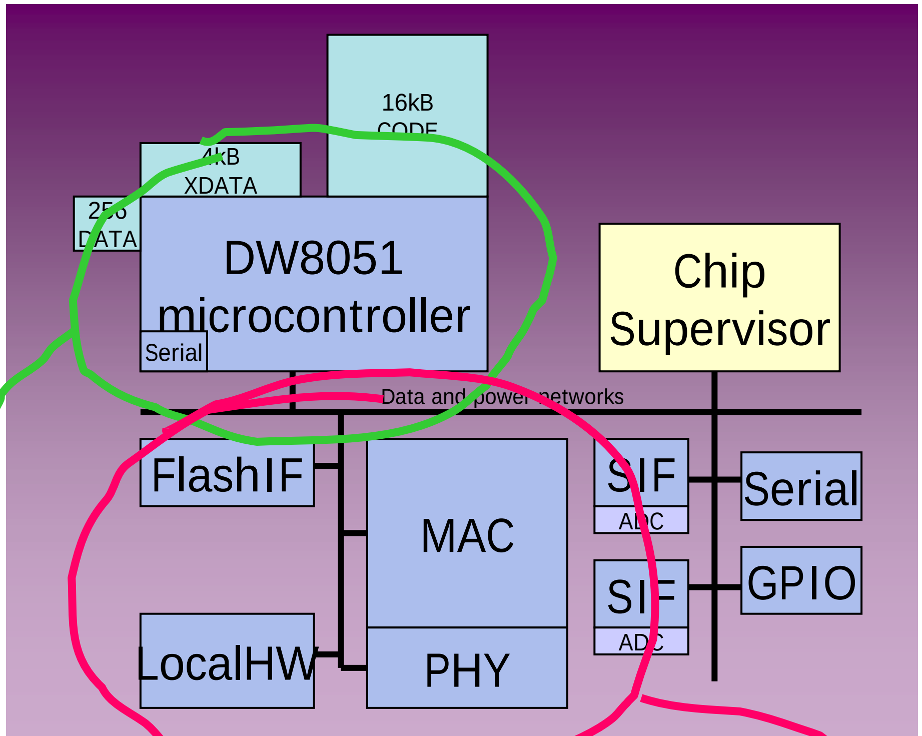
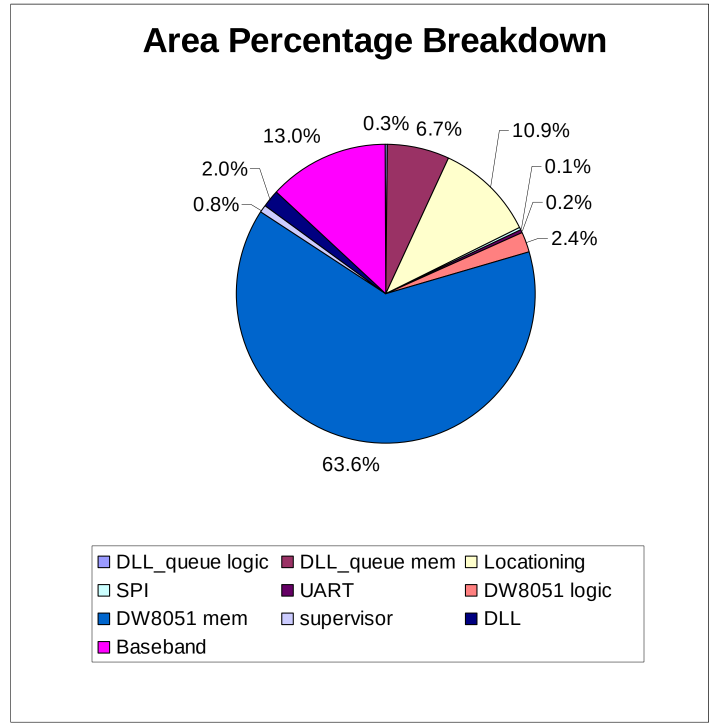
Low-Energy Digital Network Processor





Simplicity rules:

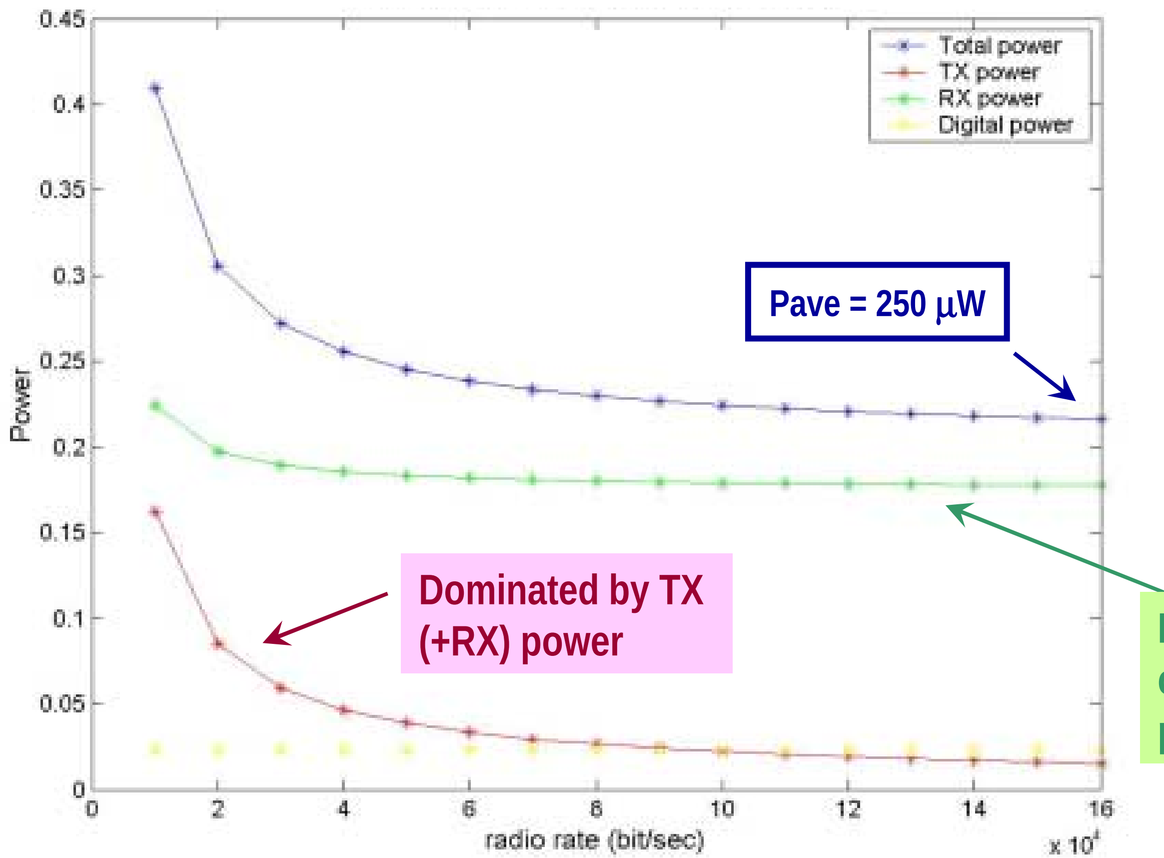
- simplest possible processor
- hardwired accelerators when needed
- lowest possible clock frequency
- operational voltage: 1V (130 nm CMOS)

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
- Synchronization using cycled receiver with Ton/T = 0.1

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

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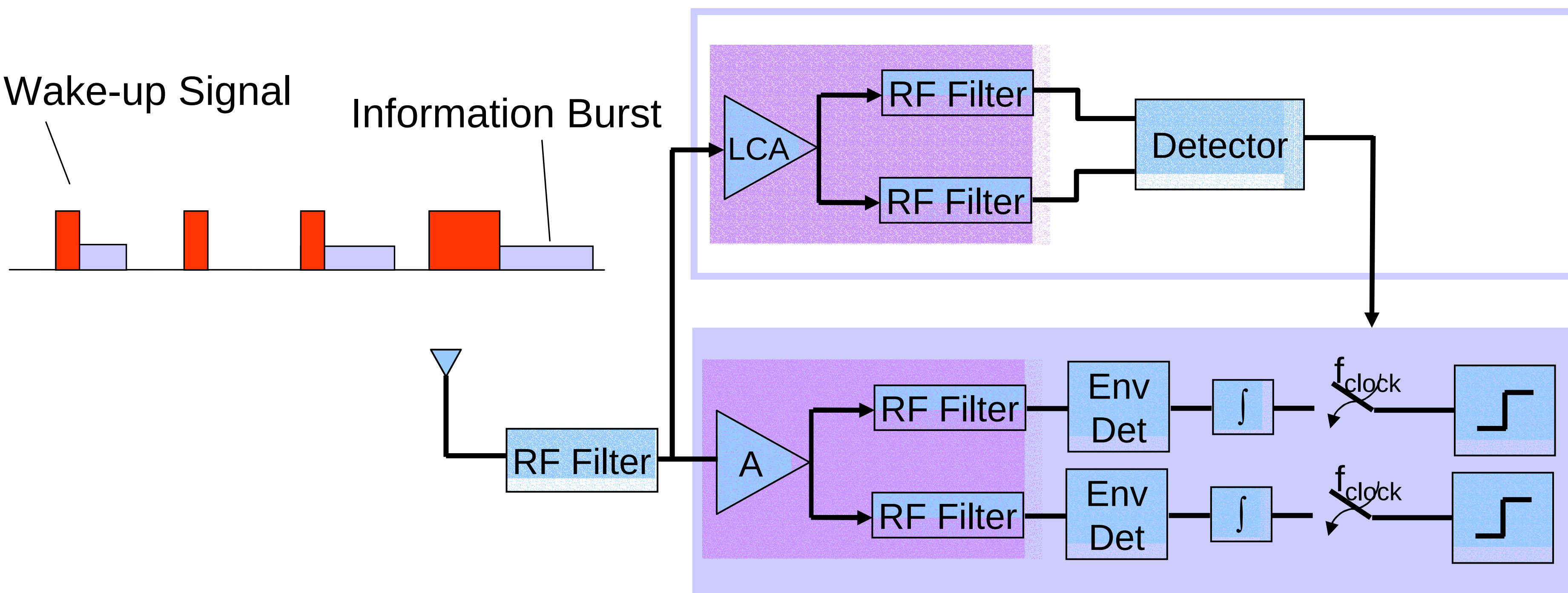
The Reactive or Wake-Up Radio

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



Shifts Burden to Transmitter
Reduces monitoring power to < 10 μW
Other Approaches: Cycled Receiver using Beaconing

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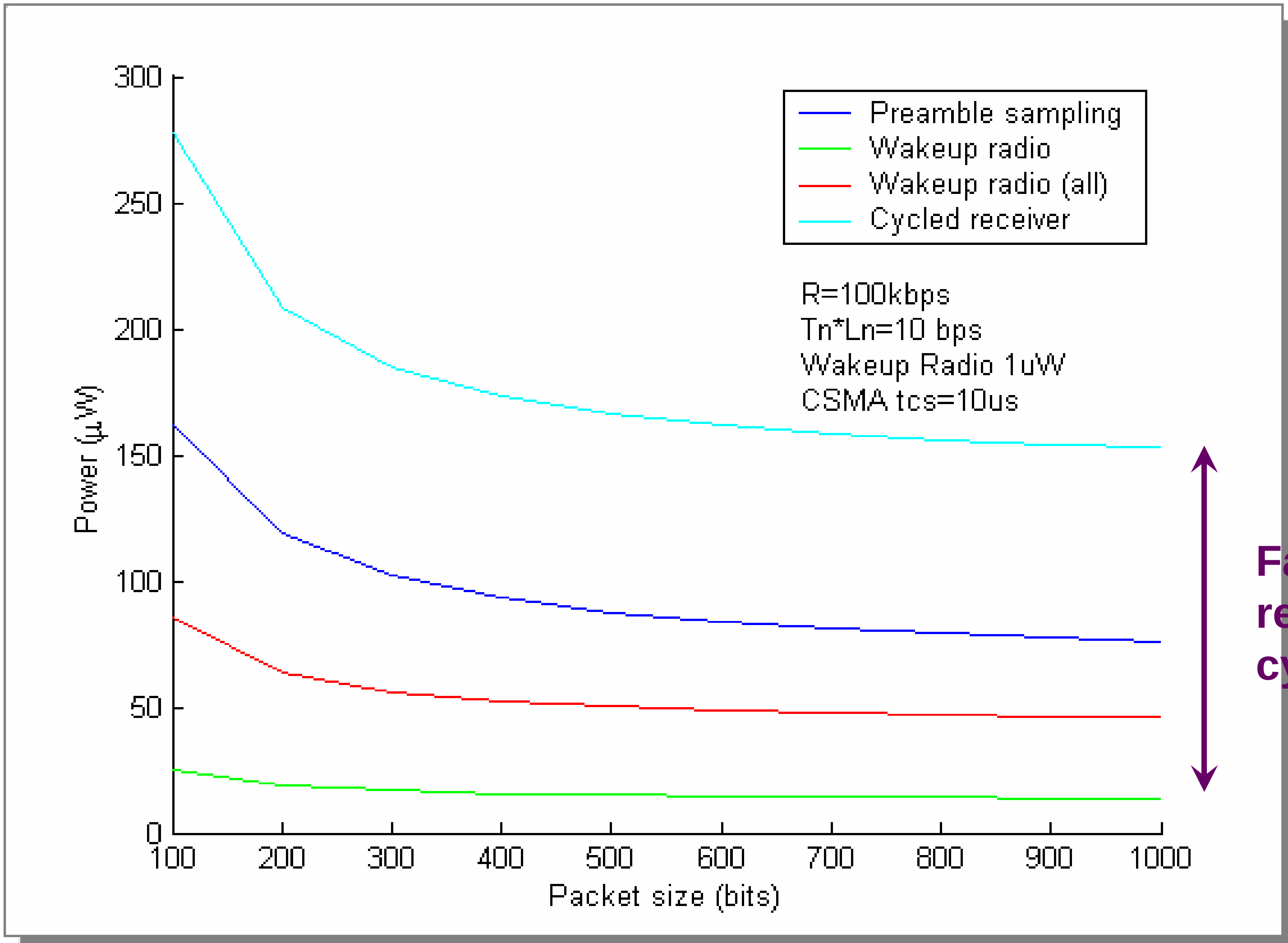
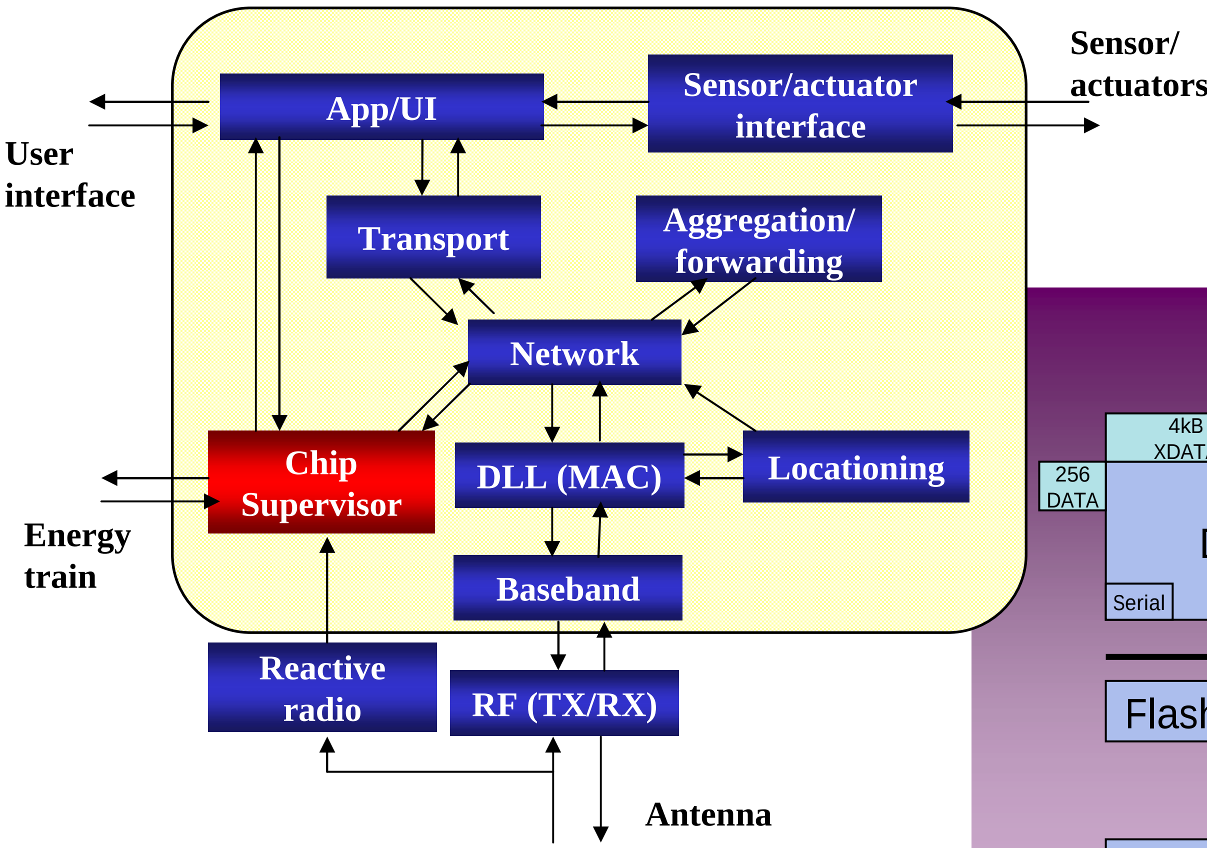
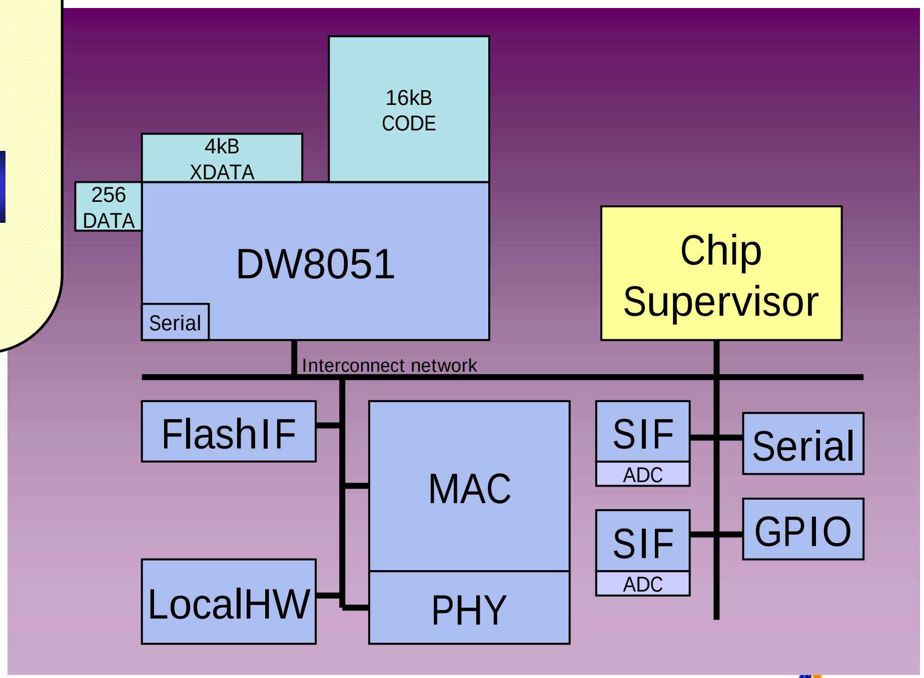
The Impact of the Wake-Up Radio



Factor 5 to 10 reduction over cycled receiver

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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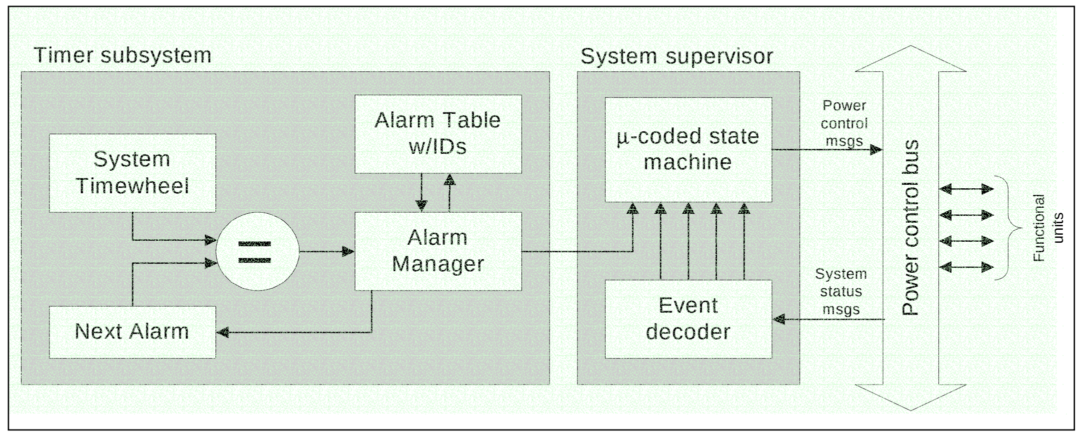
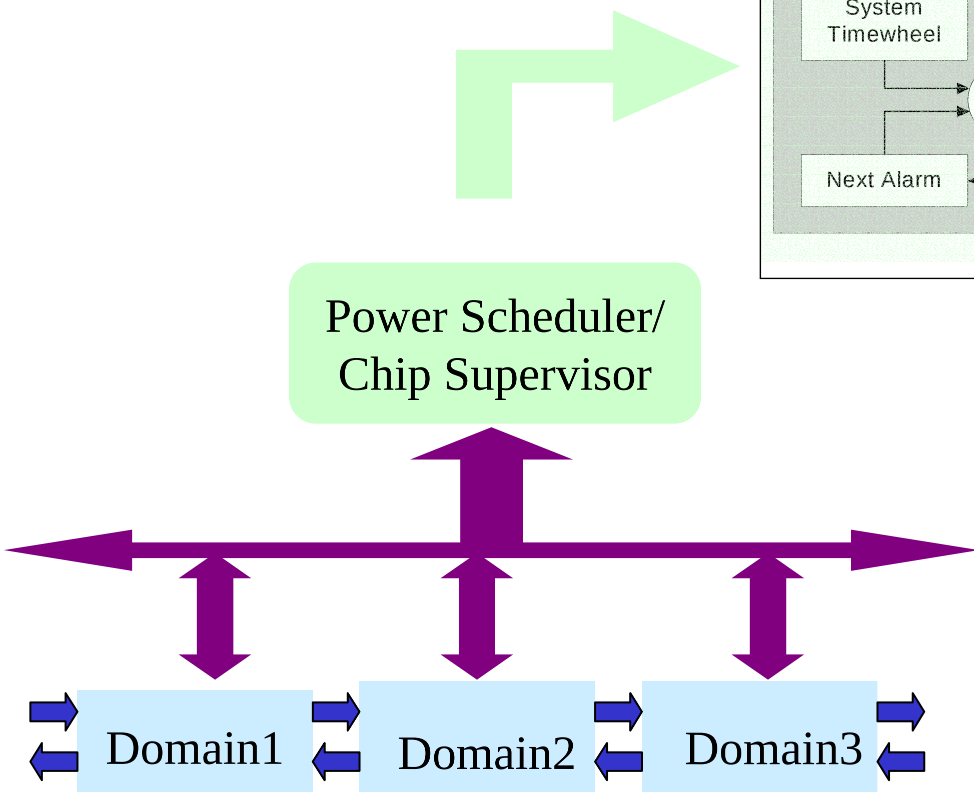
Introducing "Power Domains (PDs)"

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

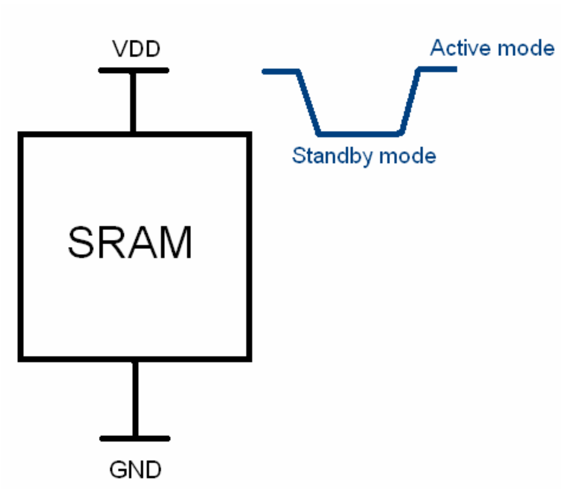


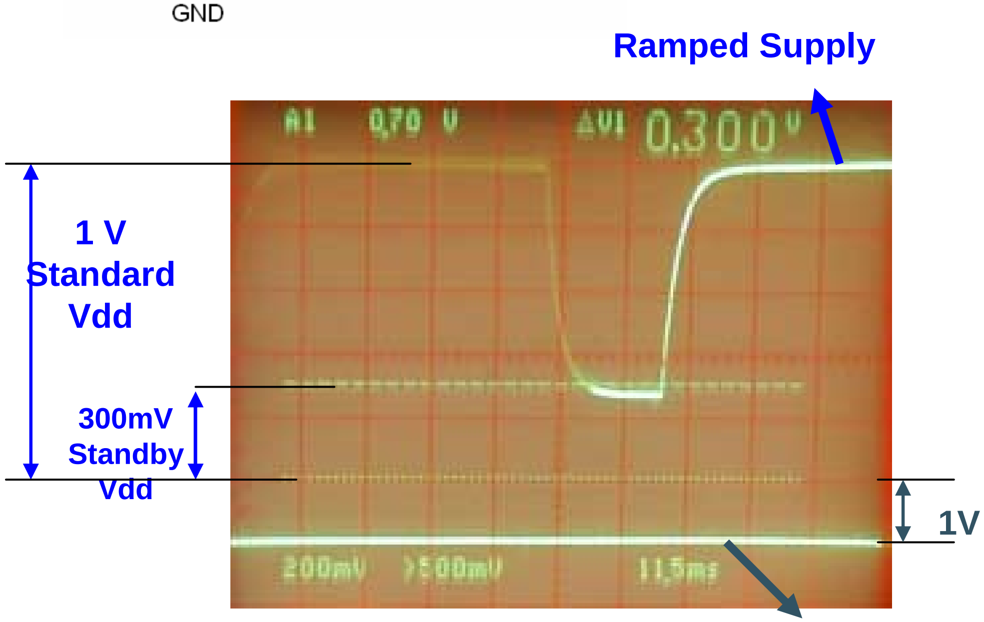


Chip Supervisor (or Chip O/S)

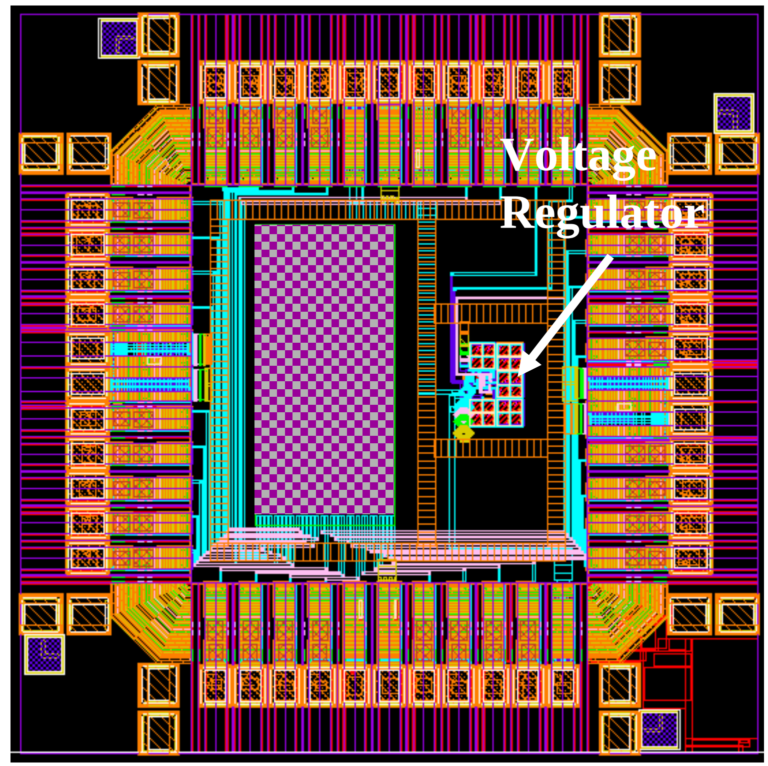
- **Maintains global state and perspective**
- **Maintains system timers**
- **Alerts blocks of important events**

Power Domains — State-Preserving Power-Down





Memory Data Bit 4 @
Address 0xFFh



1.3 mm² SRAM Leakage Control Test Chip

(0.13um Process, with 4K bytes SRAM embedded)

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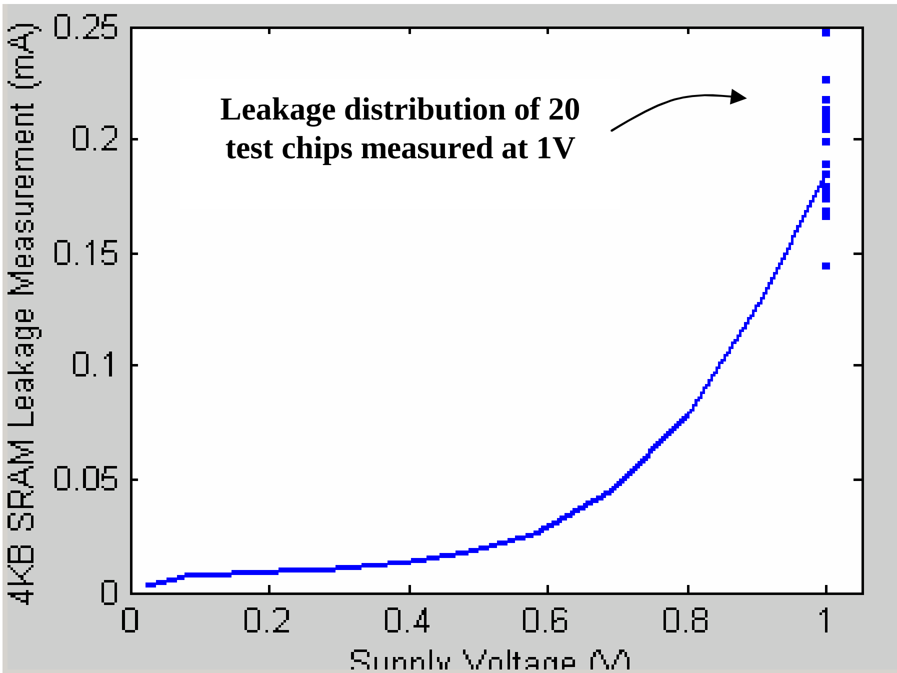
SRAM Leakage Measurement Result



0.13um 4K byte SRAM leakage measurement result

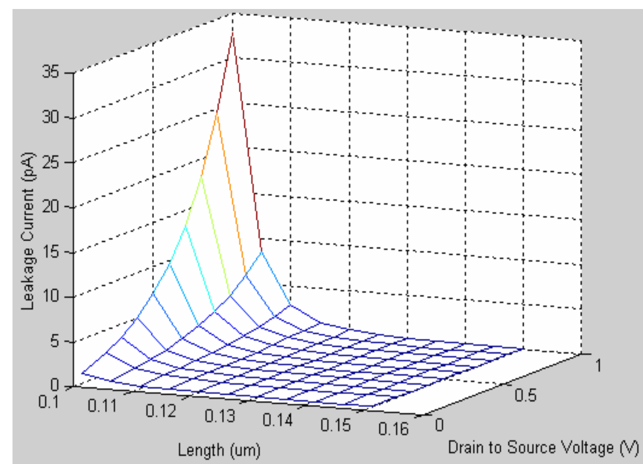
Data Retention Voltage:

80 – 250 mV (mean 180 mV)

Leakage Current (1V → 0.3V):

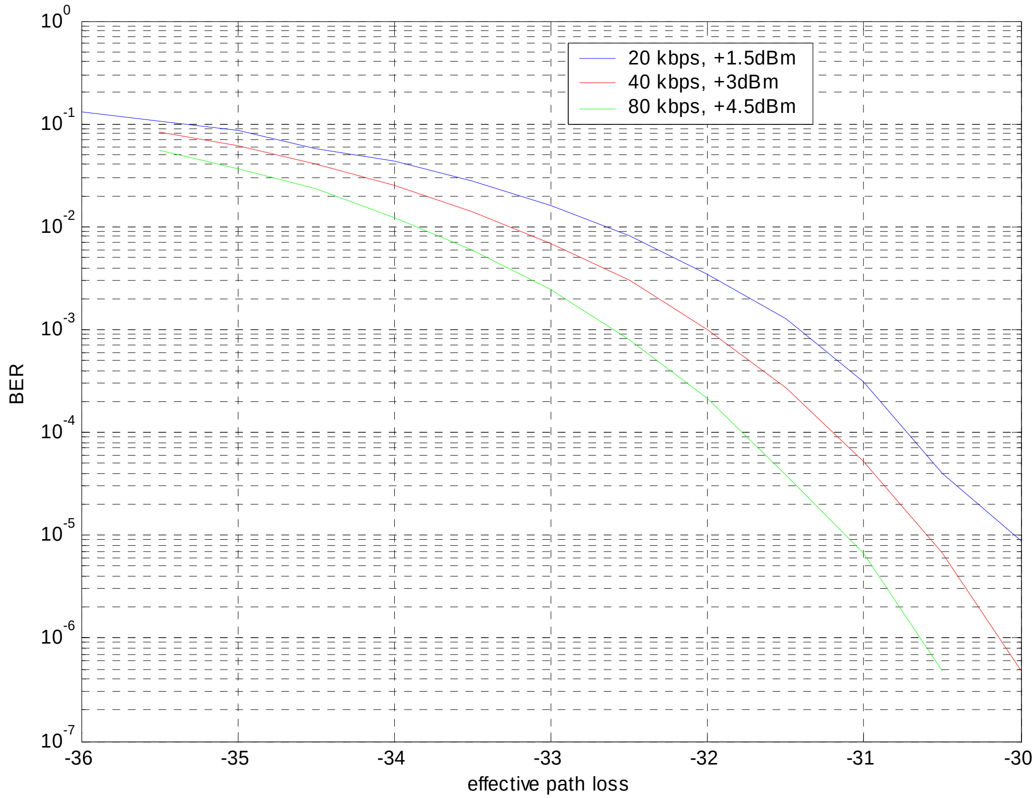
Reduced by 97%!

Discrepancy between simulation and measurement. Leakage current increases **exponentially** with Vdd due to DIBL **and channel length variation**.



Short channel device V_{TH} and leakage dependency on length and V_{DS}

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



Simulated response of PicoNode radio

- **Small Change in Path Loss Has Dramatic Impact on Transmission Quality**
  - Channel is either "good" or "bad"
- **Reducing Symbol Time (or Increasing Data Rate) Reduces Energy/bit for same QOS**
  - Factor 2 reduction in symbol time for 1.5 db in path gain
- **Go for fastest possible radio that simple scheme allows (limited by ISI)**

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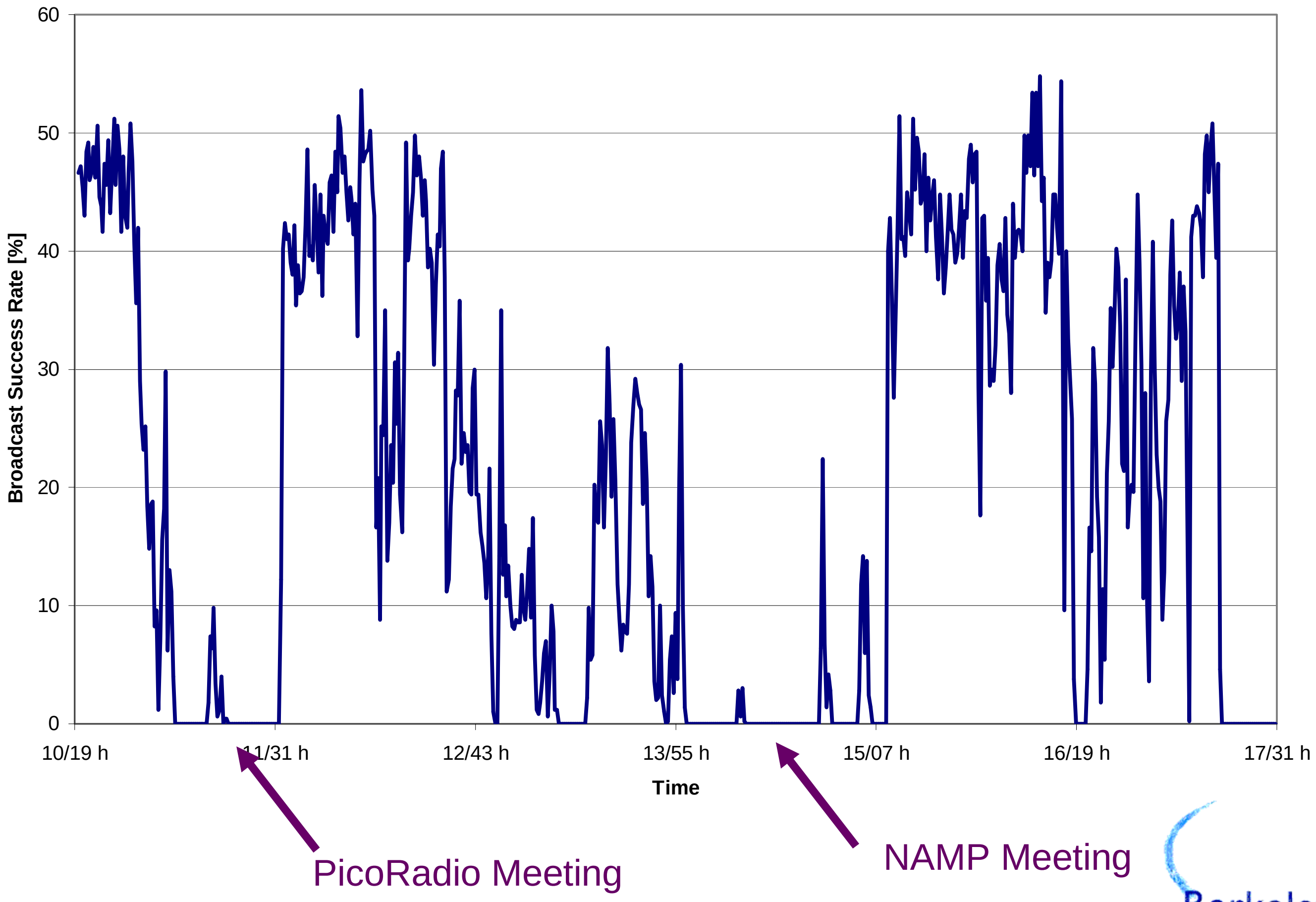
The Variability of Link Quality

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



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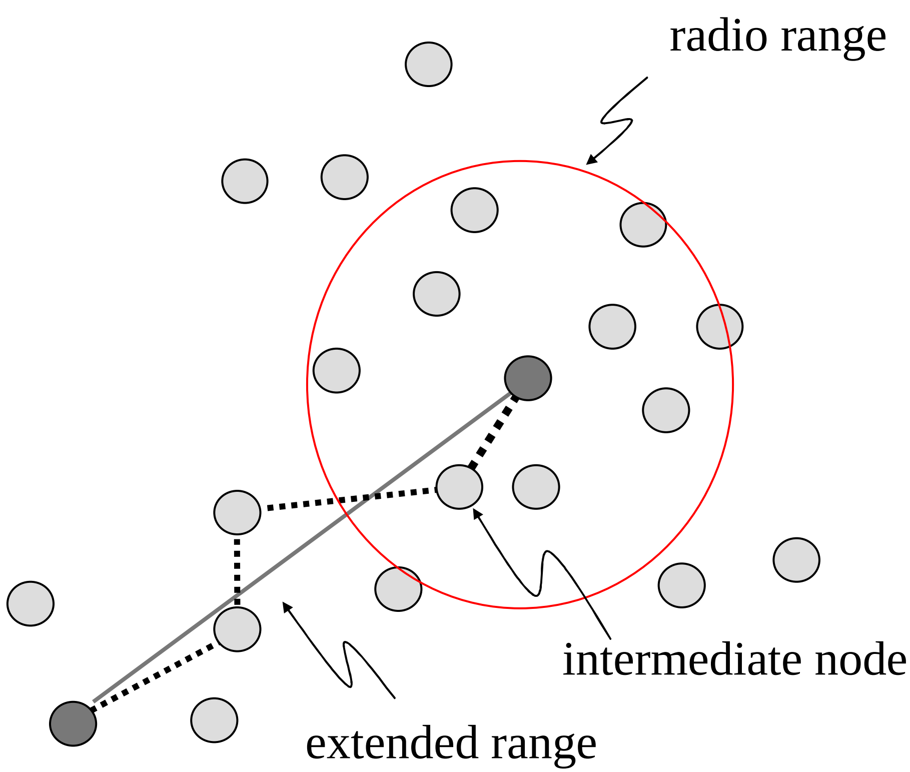
Providing Diversity

- **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**
  - For instance, require channel estimation
- **A better approach: utilize the system properties!**

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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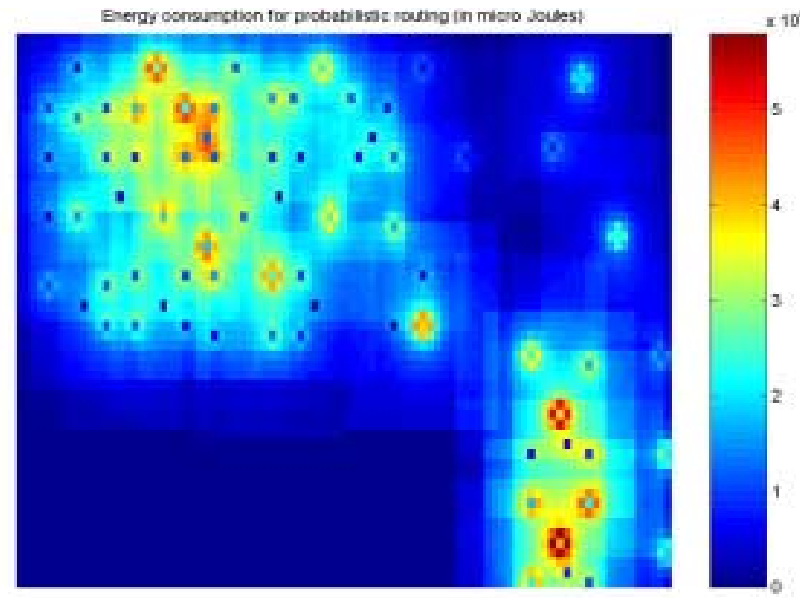
Not Networking as Usual

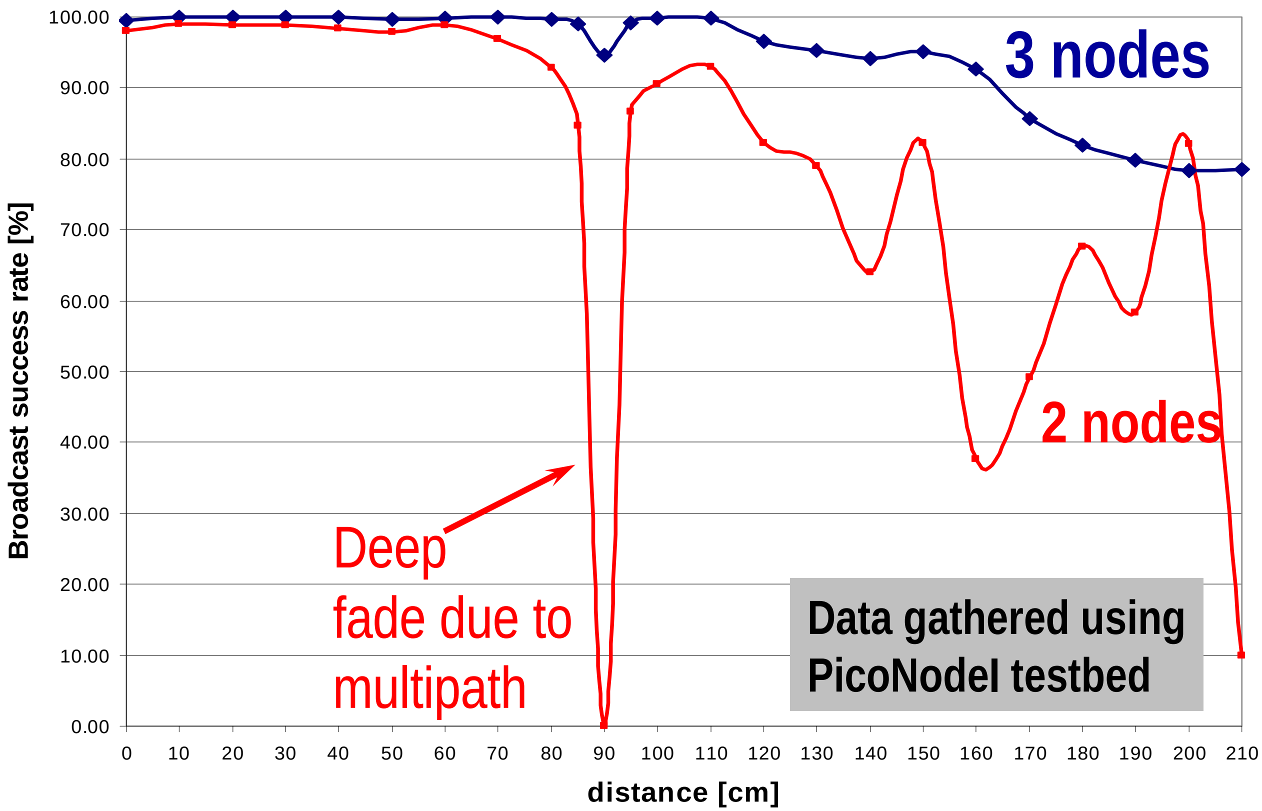
- **Sensor Networks Behave as Distributed Databases**
  - Expressed in terms of **queries** *(not in terms of the nodes generating or requesting data)*
  - *Example: "Give me temperature information in the kitchen"*
- **Information "diffuses" from sources to destinations via a sequence of local interactions, pruned by geographic information**
- **While spreading energy dissipation evenly over the network**
- **Exploiting the redundancy and the variability in the wireless data links**



Energy-aware routing

Improve robustness by choosing link connection that is available – this is, utilize spatial diversity

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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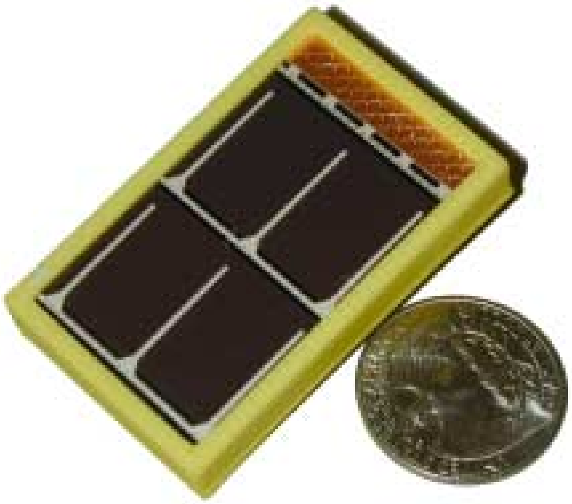
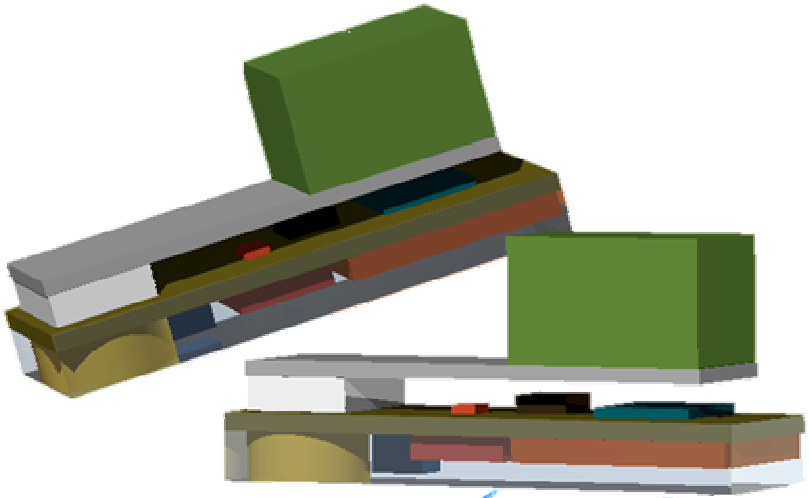
PicoNode: The first sub-milliwatt sensor node



Version 1: Light Powered



Version 2: Vibration Powered

Size determined by power dissipation

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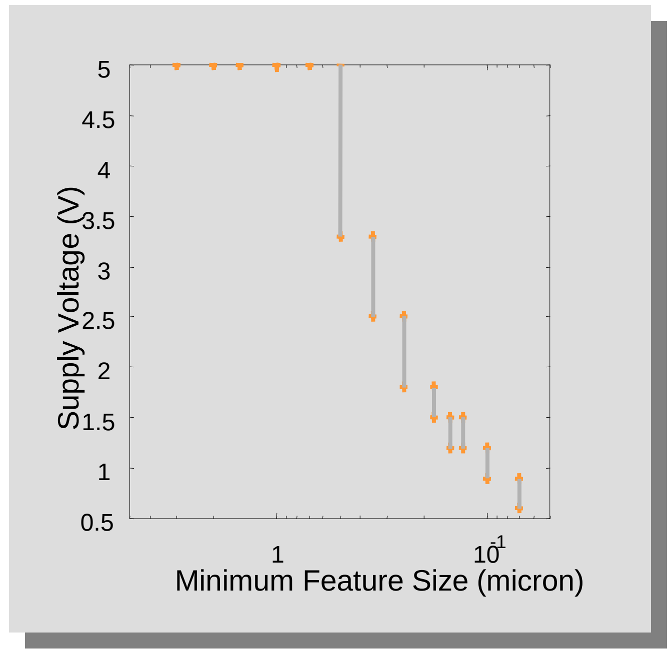
The Road Forward: Computation in the Ultra-Low Voltage Space

- **Power dissipation the main roadblock towards further integration and size reduction!**
- **Aggressive voltage scaling seems to be the only plausible answer**
  - Drain-source leakage a major fraction of power dissipation – direct function of supply voltage
  - Gate leakage one of the main emerging challenges – again, a very strong function of supply voltage
- **Below 500 mV design offers opportunity to reduce power dissipation of mobile sensor nodes by other major fraction**



SIA Roadmap not aggressive enough?

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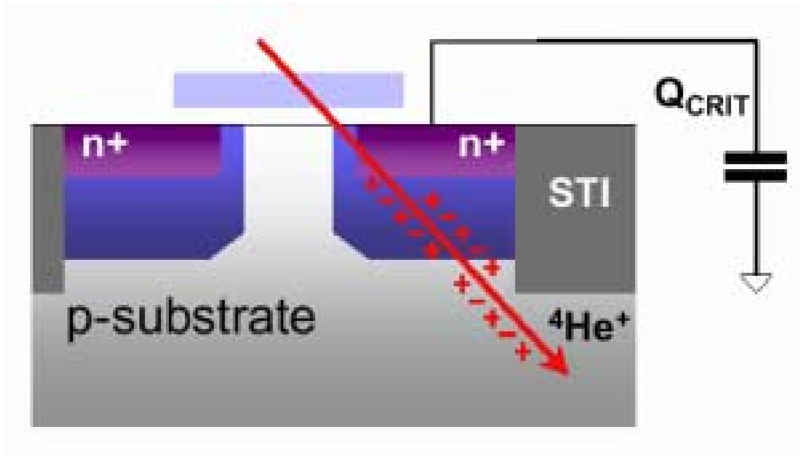
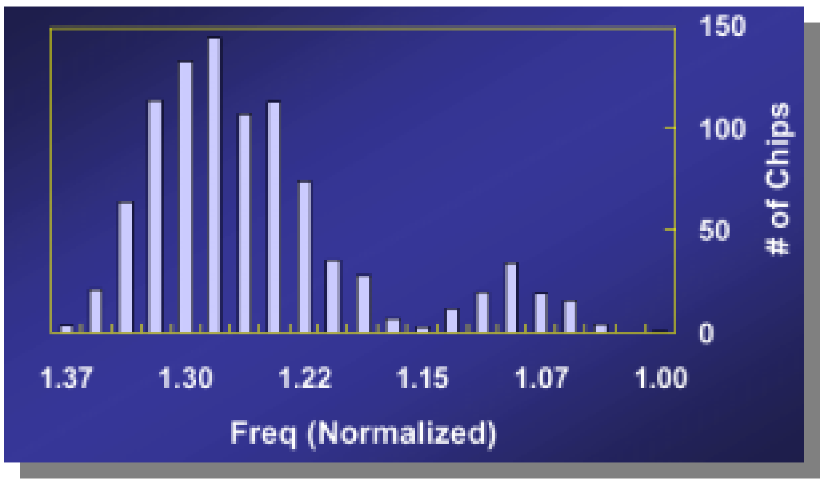
Computation in the Ultra-Low Voltage Space
How low can we go?

- **While many noise sources scale, some do not!**
  - Thermal noise
  - Soft errors

  Circuits are bound to start producing errors when supply voltages are aggressively scaled!
- **Variability of threshold voltage remains approximately constant, causing gate performance to vary widely**

➔ **Explore circuit and architecture techniques that deal with performance variations (e.g., self timed) and are (somewhat) resilient to errors!**





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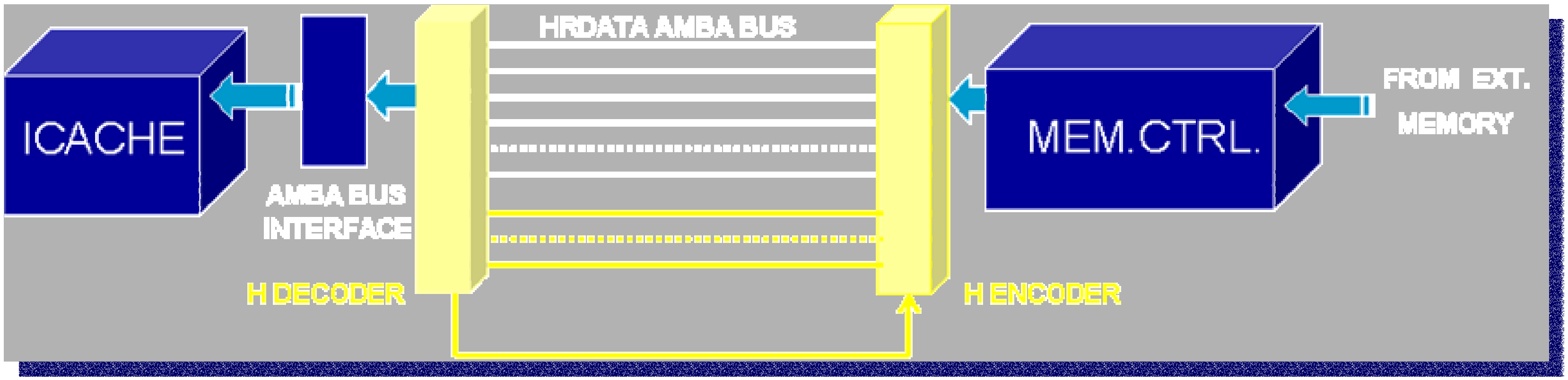
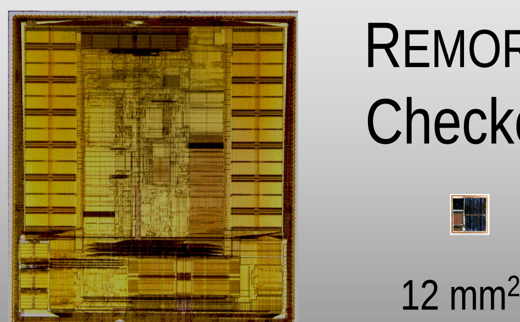
Coming Full Circle: Using Diversity and Redundancy to Combat Errors in SoC



Error-correcting Bus (N. De Michelli)

Alpha 21264



Self-checking processor (T.Austin)

Trading off energy versus yield or area

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**

MAKING ELECTRONICS WORK FOR YOU, NOT VICE-VERSA

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