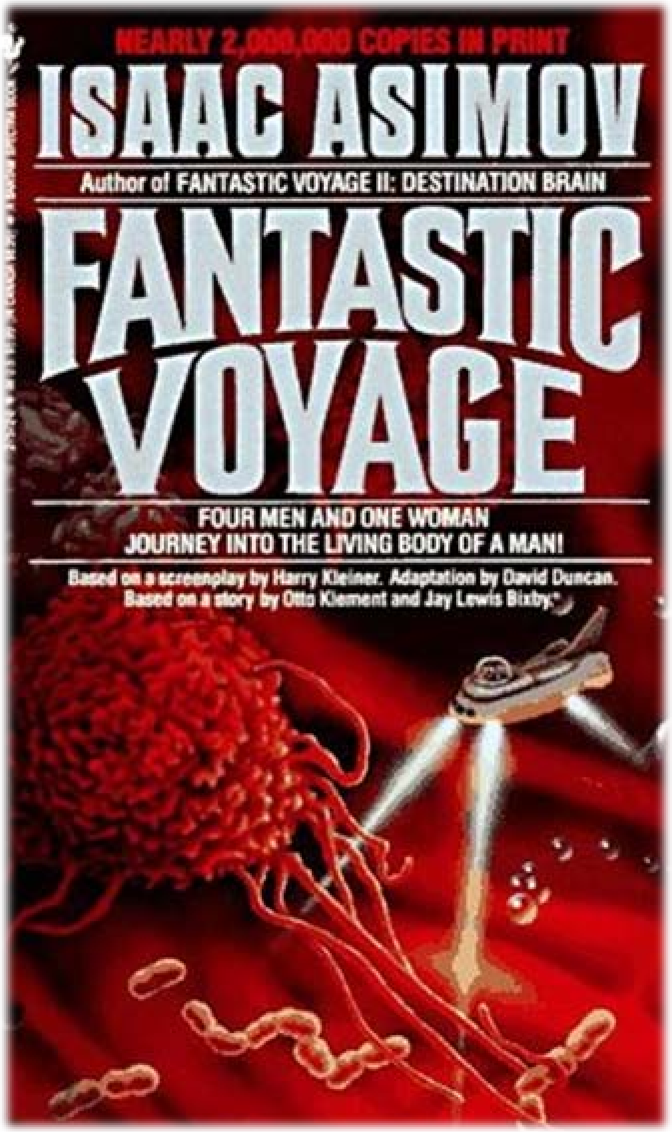

From PicoNodes to "Microscopic Wireless"

Jan M. Rabaey

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S. Gambini, A. Kumar, Y.M. Li, T.T. Liu, M. Mark,
N. Pletcher, J. Richmond

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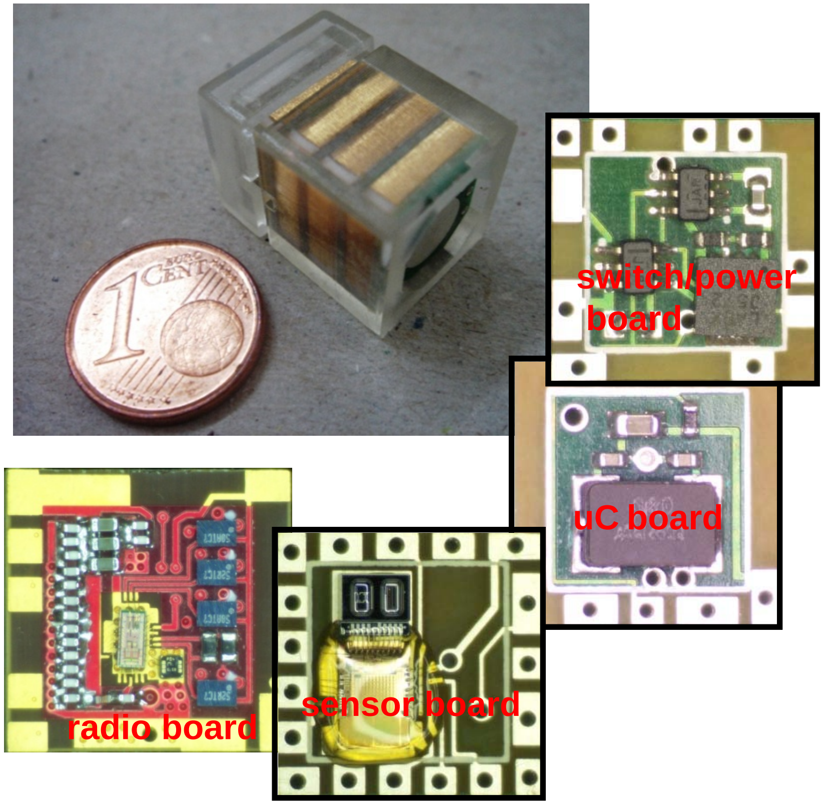
The UCB PicoNode (Anno 2006)



Magnetic shaker

Energy-scavenged pressure, temp and acceleration (3D) sensor node

UCB Picocube

A modular approach to miniature wireless

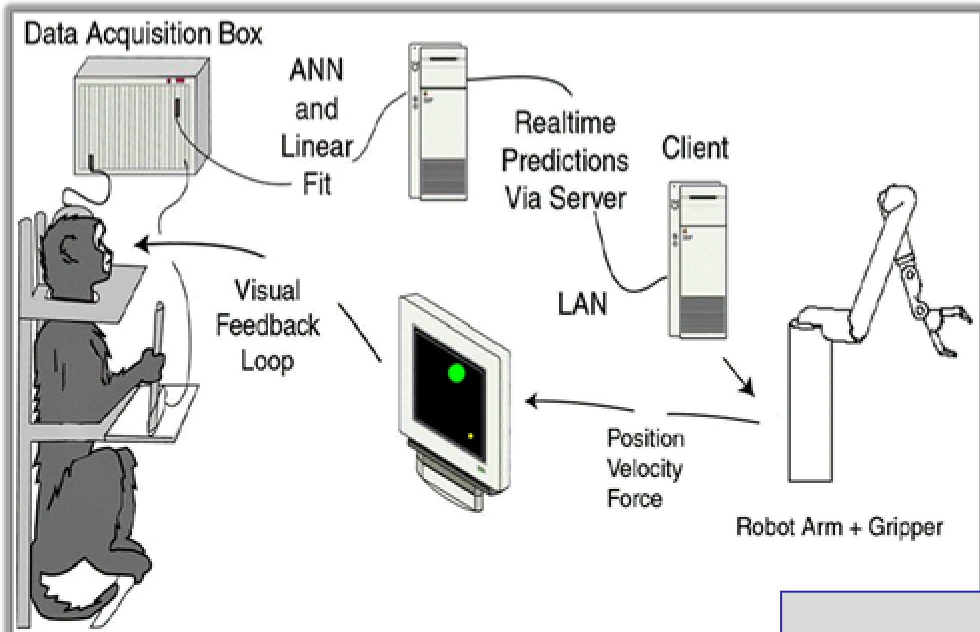
1 cm^3

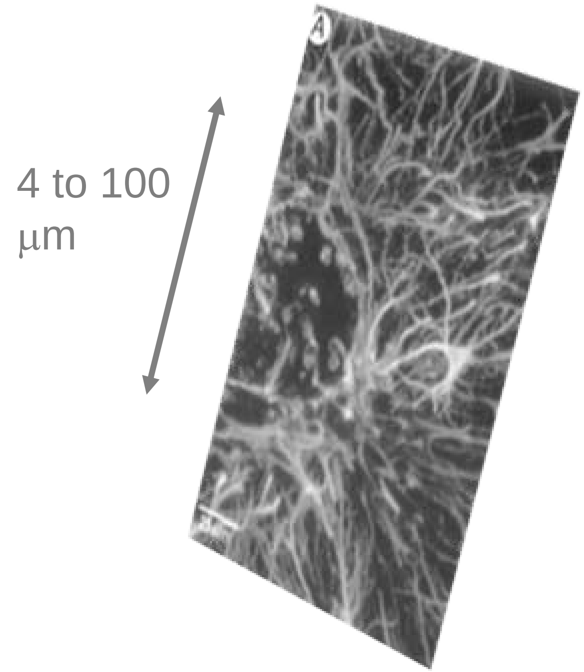
6-10 μW P_{avg}

The Microscopic Wireless Challenge

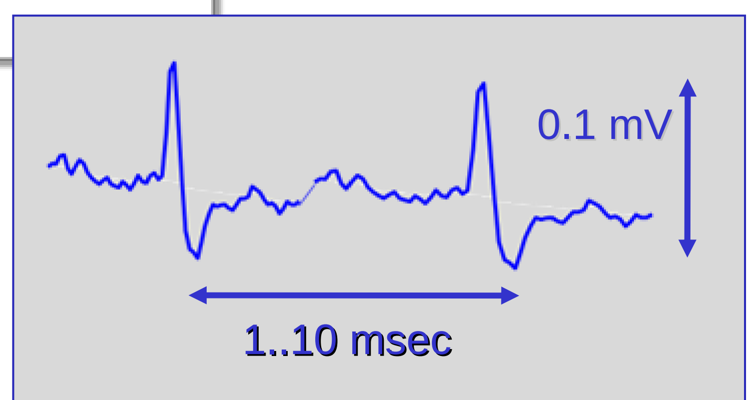
3 orders of magnitude in size and power reduction

Observing neural activity





Need to extract timing of synaptic pulses



State of the Art

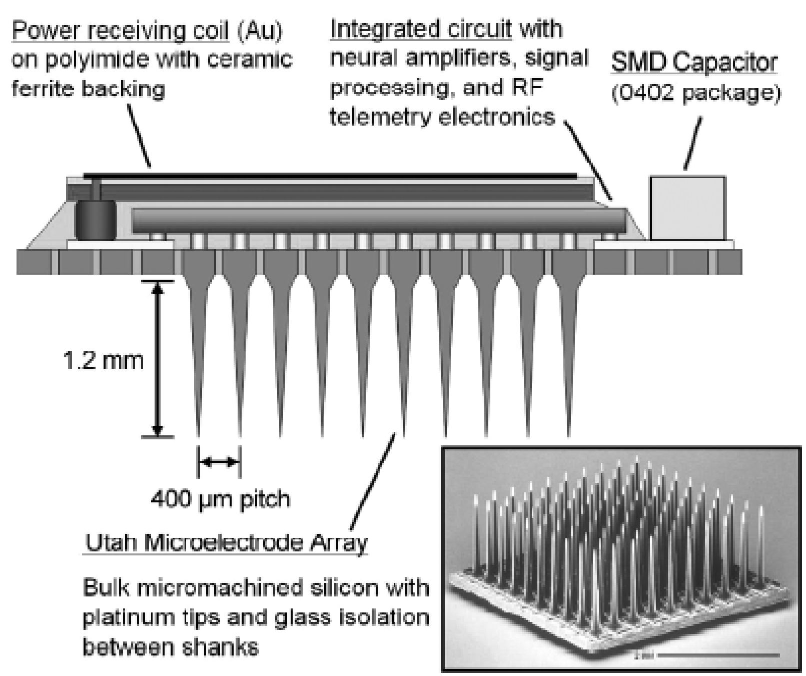
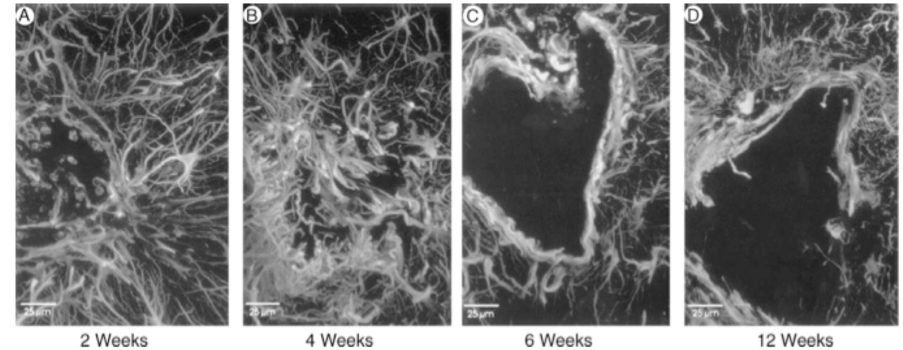


Fig. 1. Complete Integrated Neural Interface (INI) assembly concept. Inset shows Utah Microelectrode Array.

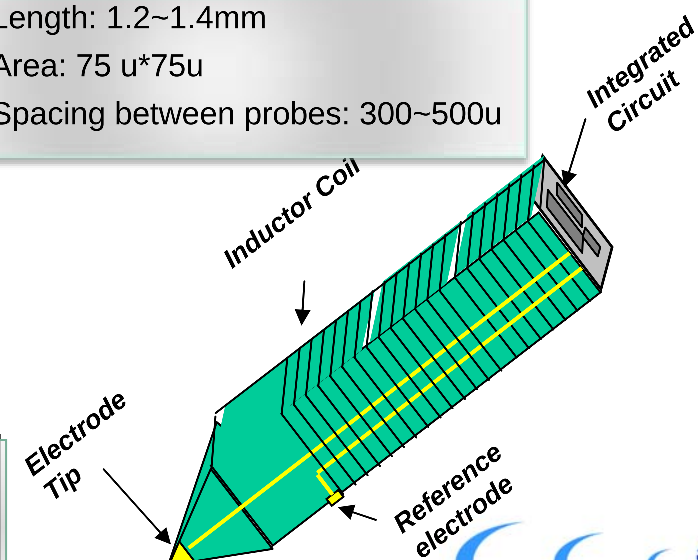
[Reference: "A Low-Power Integrated Circuit for a Wireless 100-Electrode Neural Recording System", R. Harrison et. al., JSSC January 2007]

But: fixed arrays may cause scarring



Option: smaller, single wireless probes

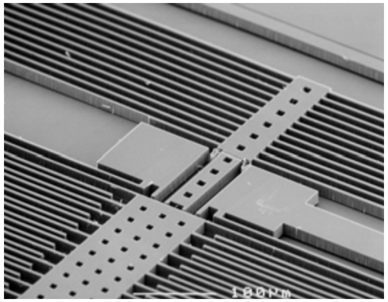
- Length: 1.2~1.4mm
- Area: 75 u*75u
- Spacing between probes: 300~500u

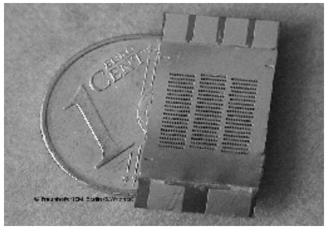


- Depth: ~1cm;
- 32kS/s; 4~8 bits;
- Control latency: 50ms;
- Stimuli: ±1V x 200us.

[Courtesy: J. Carmena, UCB]

What can one do with 1 mm^3? (Extrapolated from the past …)

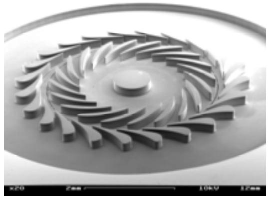




Energy storage

	μW
Solar (outside)	15
Air flow	0.4
Human power	0.35
Vibration	0.2
Temperature	0.04
Pressure Var.	0.02
Solar (inside)	0.01

Energy generation



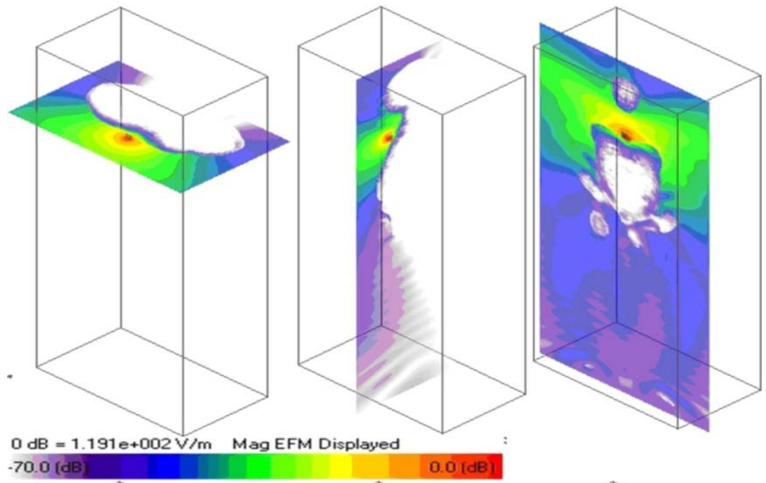
	J/mm^3	**μW/mm^3/year**
Micro Fuel cell	3.5	0.110
Primary battery	3.0	0.090
Secondary battery	1.1	0.035
Ultracapacitor	0.1	0.003

(max: 10 J/mm^3) (Ref: Cavin, Zhirnov)

0.1 μW seems to be a reasonable target number

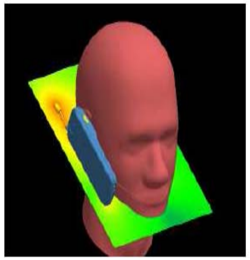
[Courtesy: S. Roundy]

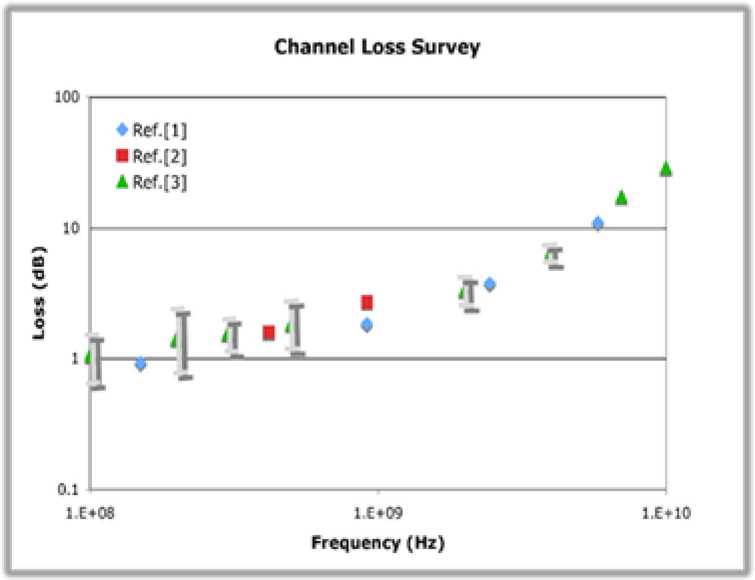
The Channel

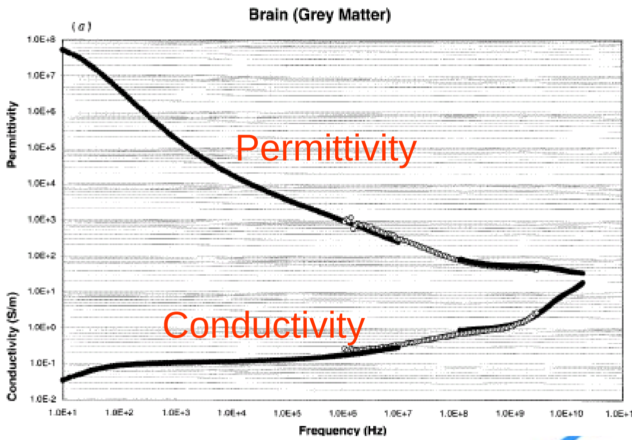


Bio-EM Capabilities

- Male and Female Human Body Meshes/Male Head Mesh with automatic adjustment of tissue parameters for single frequency calculations
- Male and Female Human Body Meshes /Male Head Mesh with frequency-dependent tissue parameters for transient wide bandwidth calculations
- Specific Absorption Rate with 1 and 10 gram averages, whole body average, locate peak SARs, follows protocol of latest C95.3 standard
- Temperature Rise in Human Body
- SAM Head for SAR for FCC acceptance
- Manual/Automatic Partial Volume SAR







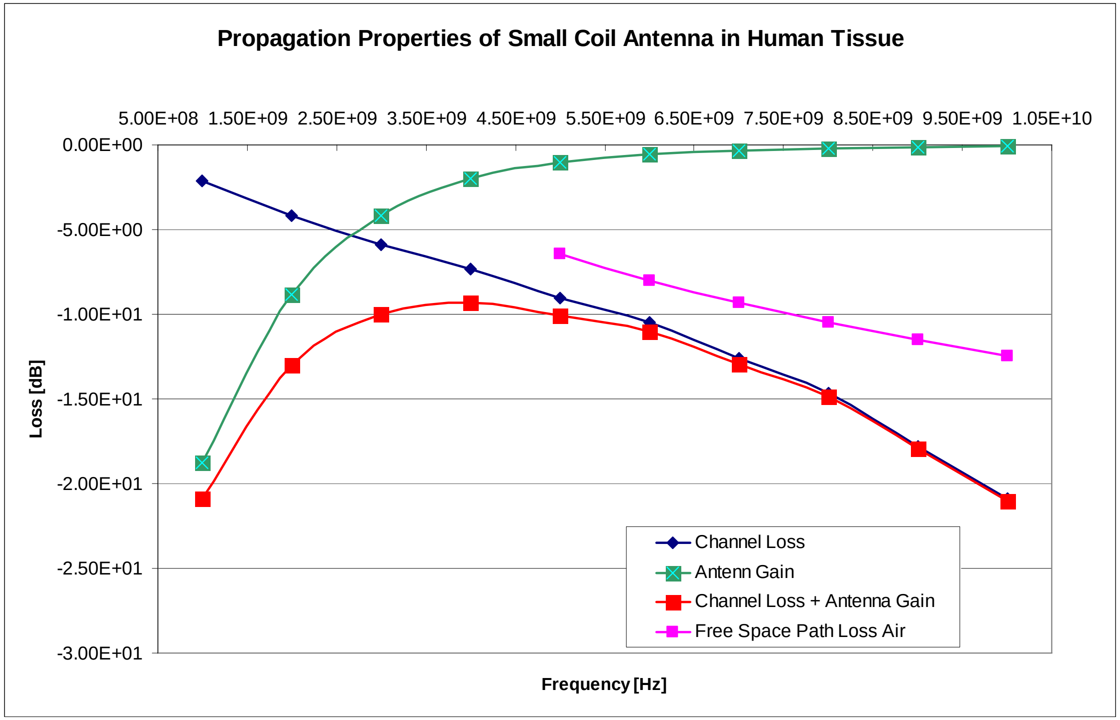
Dielectric properties of the brain [Gabriel06]

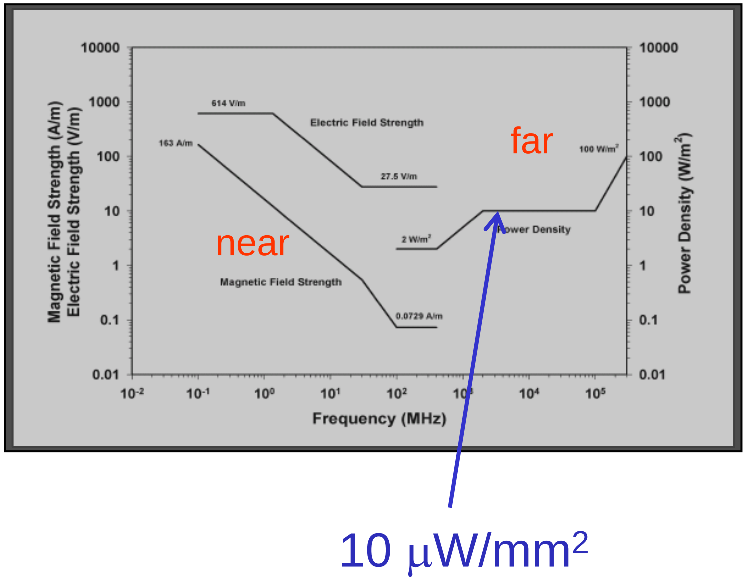
Electromagnetic Power (RF-ID like)

Challenges:

- Small coil (1 mm^2 with 1 turn) – 1 cm distance
- Large path loss in human body at higher frequencies
- Optimum at higher frequencies for smaller antennas

Maximal exposure to human body (IEEE c95.1)

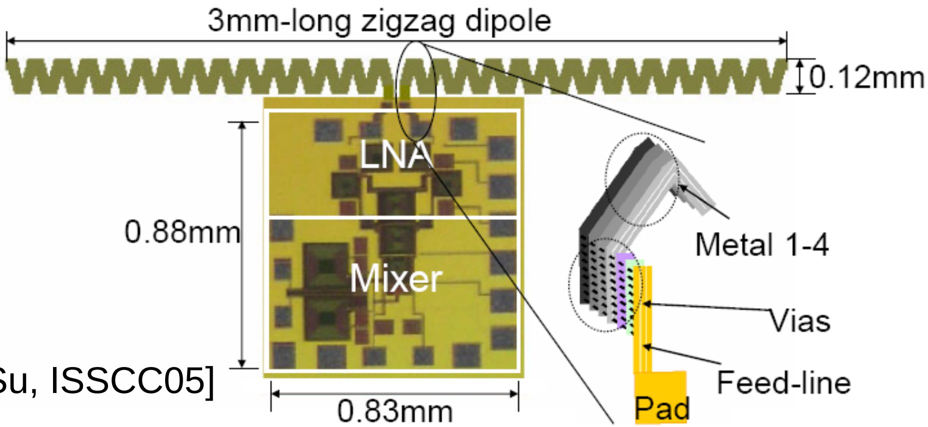




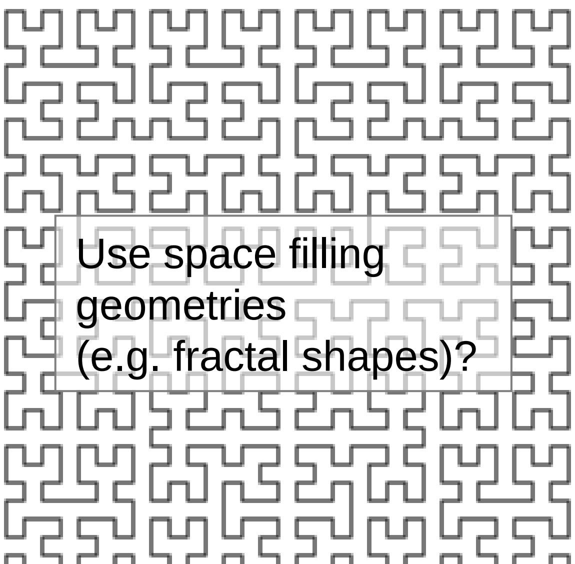
Note: These derivations are first-order

Active Communications: The Antenna Challenge

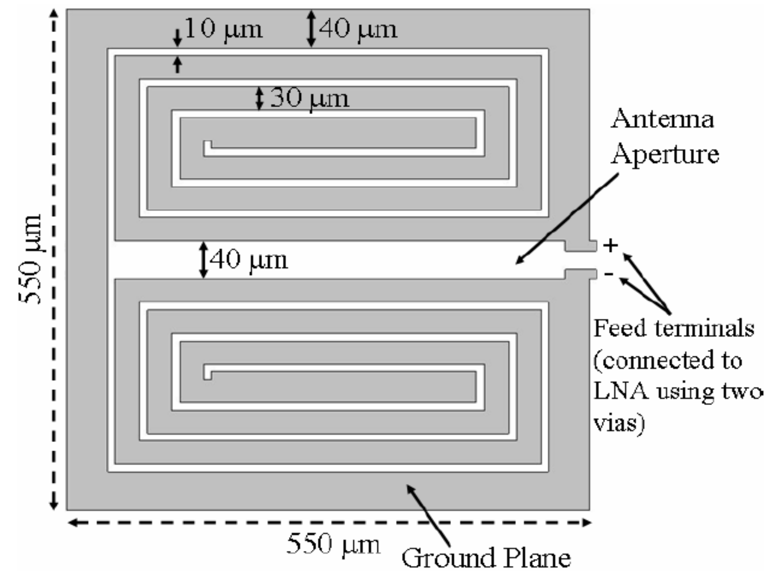
What can reasonably fit onto 1mm^2?



[Su, ISSCC05]



Use space filling geometries (e.g. fractal shapes)?

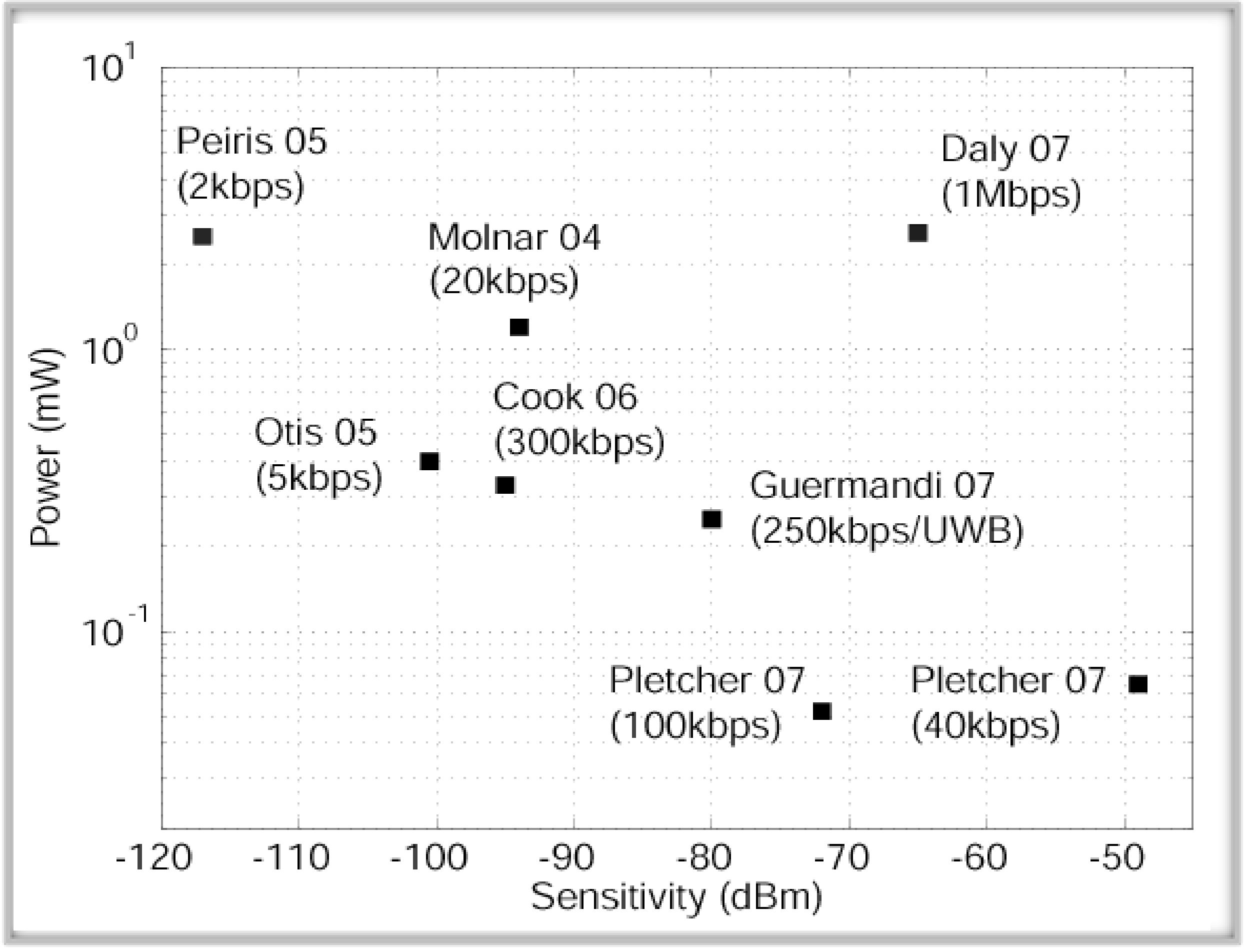


Meandering Dipole Antenna [Flynn, RFIC07]
Efficiency: 10%; Ka = 0.05, 10 GHz

Other options?

- Metamaterials
- Carbon Nanotube antenna's
- …

ULP Wireless Receivers – State of the Art



Other metrics:
Energy per useful bit

* Assumes receiver is always on (no duty cycling)

**All these receivers with the Guermandi exception are NB

Wireless Communication Challenges

Some interesting bounds

Ideal link: Modulation achieves Shannon capacity,
noiseless zero power RX, ideal TX (100% efficiency).

η = (ideal energy/bit) / (actual energy/bit)

Example1: [Chee06 TX, Pletcher 08 RX] Low sensitivity ULP receiver

η = (Link margin * kT ln 2) / ((P_{Tx} + P_{Rx}) / R)

= (72db * 2.9e-21) / (1.05mW/100e3)

= -53.6 dB V

Example2: [Chee06 TX, Otis 05 RX] High sensitivity Low-rate receiver

η = (Link margin * kT ln 2) / ((P_{Tx} + P_{Rx}) / R)

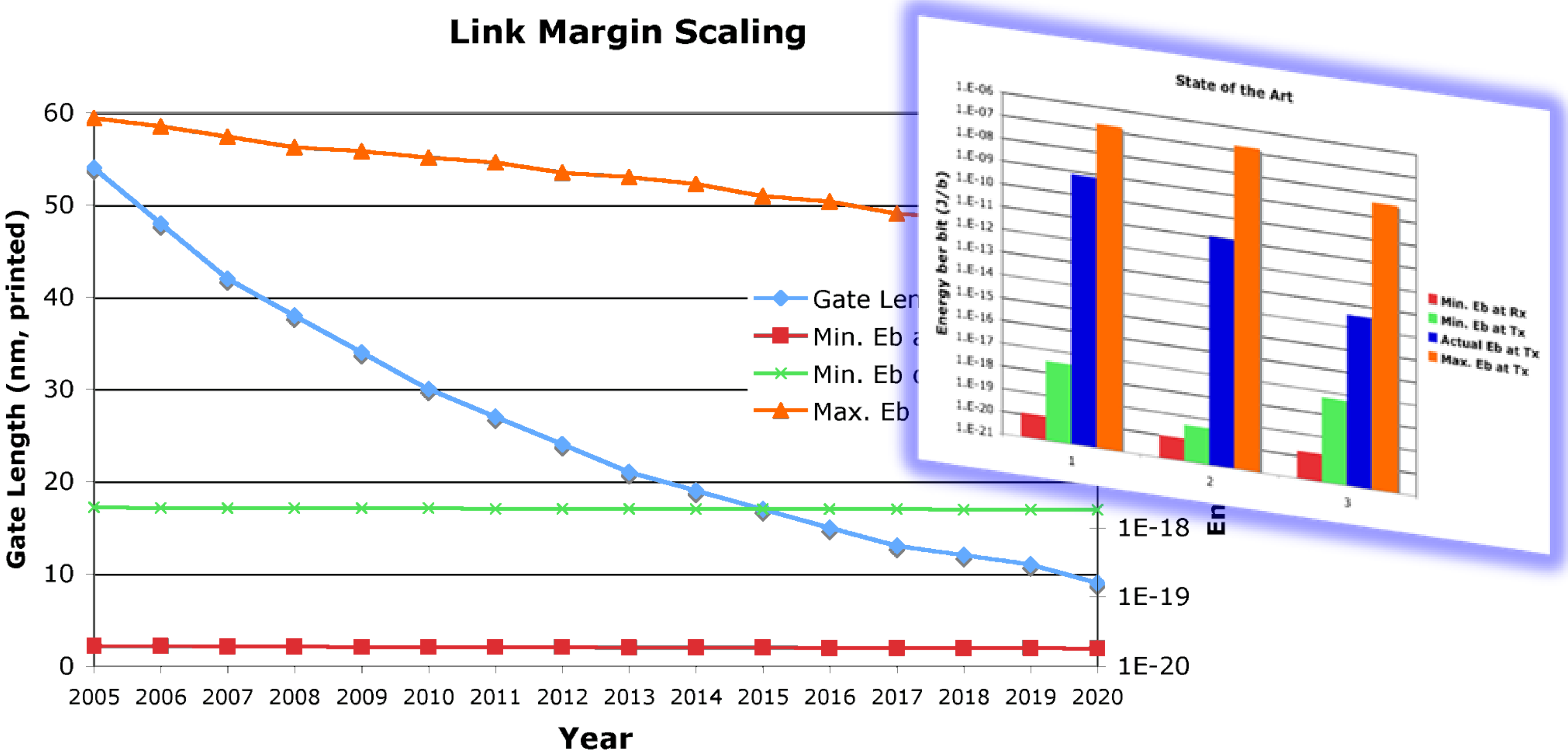
= (100db * 2.9e-21) / (1.55mW/5e3)

= -40.3 dB V

Challenge – Hard to get efficiency of TX above 50 %,
drops with reducing radiated power

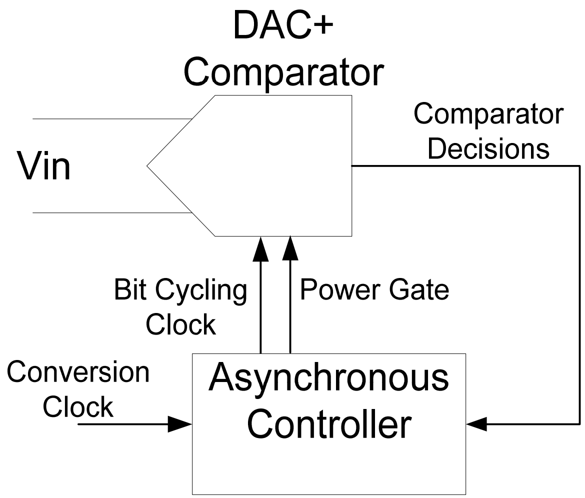
[After analysis by B. Cook, PhD, UCB]

Wireless Communications (Pulse Based)



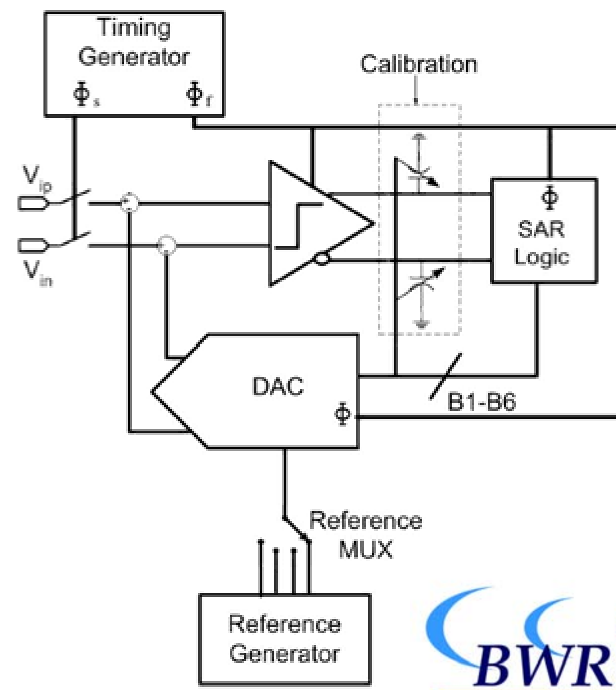
Assumes ideal synchronization, Shannon capacity, no receiver noise, BER = 10^{-4}

Mixed-Signal – Some Reference Points



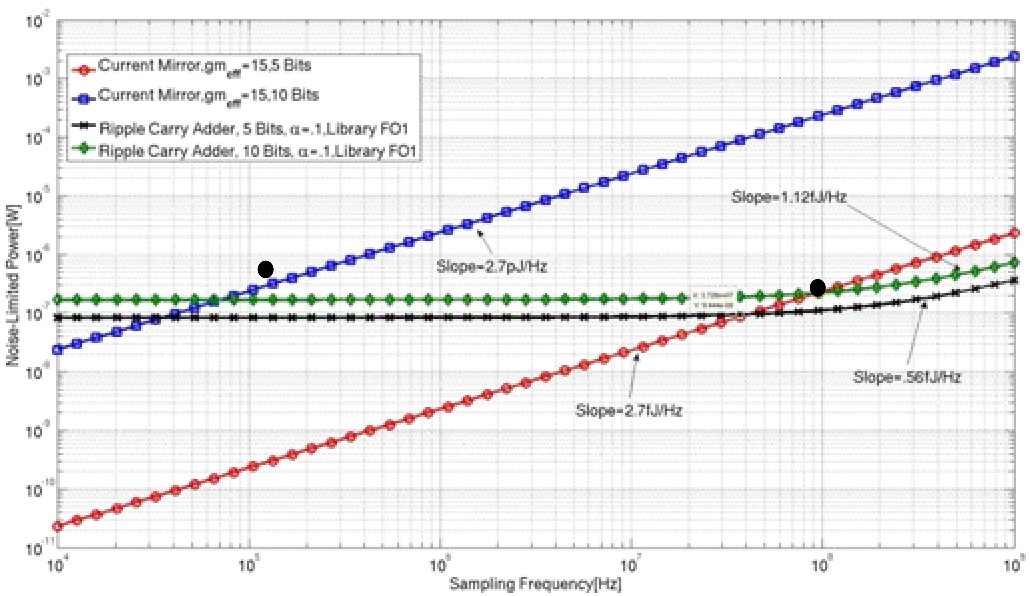
Fs	ENOB	Pd	FOM
<50MS/s	7.8Bits	720uW	65fJ/conv
1 MS/s	5.1 Bits	17 uW	500fJ/conv

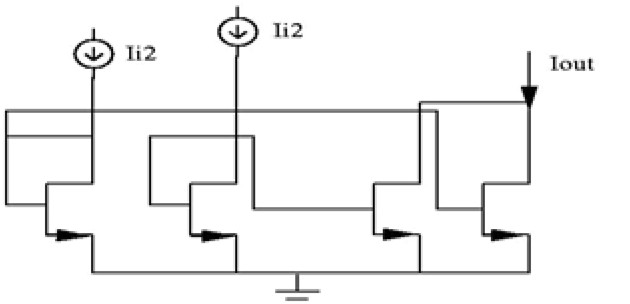
- Leakage is the largest challenge in fine-line processes
- Keep clock rate high (multiplexing) to keep the transistors efficient and avoid charge leakage [Gambini,Rabaey, JSSC,Nov2007]
- Do all the computation as fast as possible and power gate [Similar to IMEC, ISSCC2007]



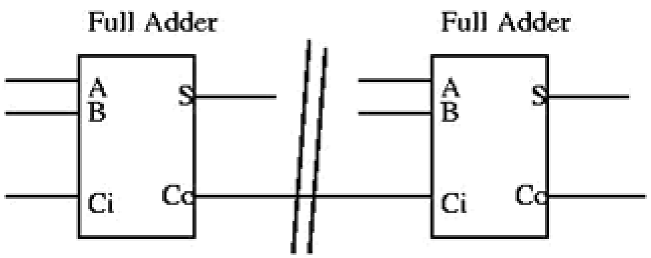
Mixed-Signal Bounds

- At low resolution, power dissipation not noise limited
- Simple architectures preferable (e.g. SAR)
- **Increasing leakage of digital makes analog more attractive**
- Must explore architectures that allow ULV operation

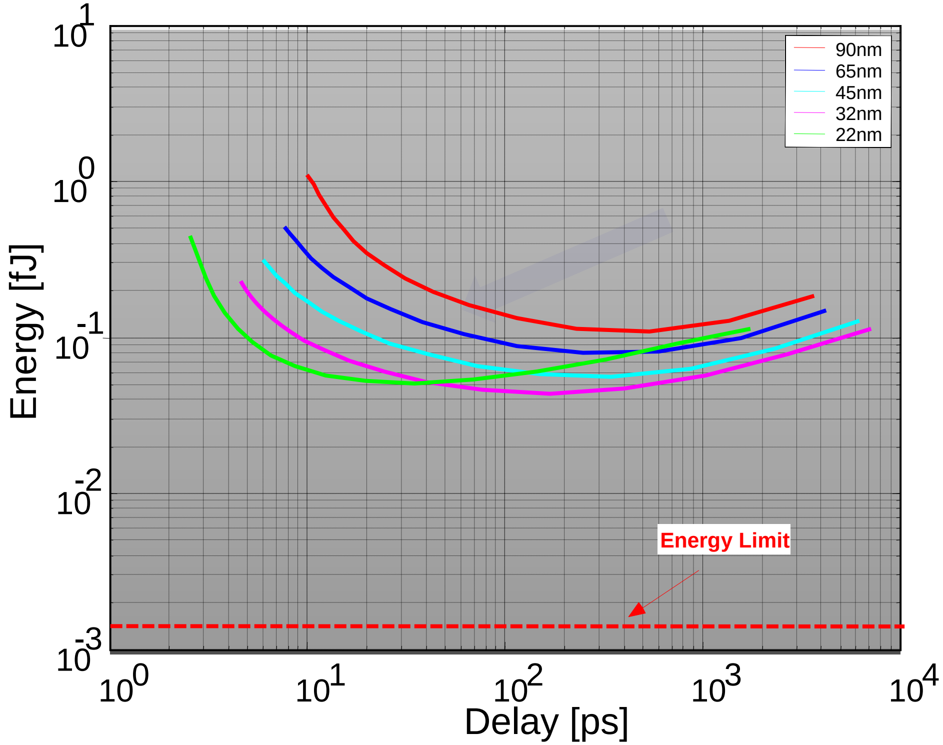




versus



Digital Computation – Aiming at kTln2?



Energy-delay curves for inverter
- 423 stage ring oscillator
- Using predictive models
- Thresholds set to nominal levels

Minimum energy/inversion scales with factor 3 (down to 40 aJ/operation) (Less than linear)

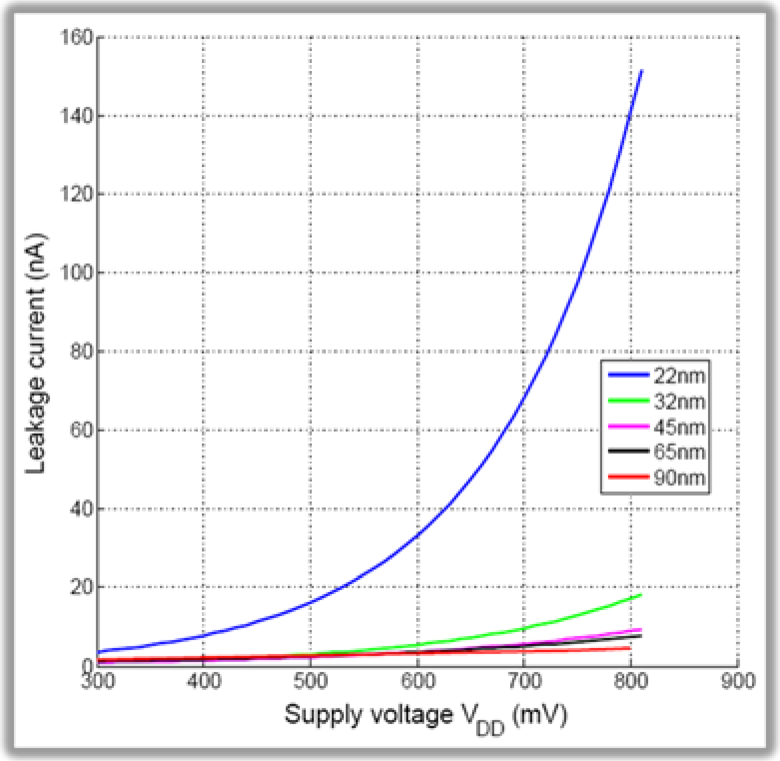
Still factor 40 above energy limit (set at 500 kTln(2))

Delay scales with factor 2 (excluding 22 nm)

Are we leaving crumbs (loaves) on the Table?

Memory

- **1 kbit SRAM memory**



Nominal retention power (for 400 mV standby DRV)	
90 nm	0.32 μW
45 nm	1.49 μW
32 nm	1.75 μW
22 nm	7.82 μW

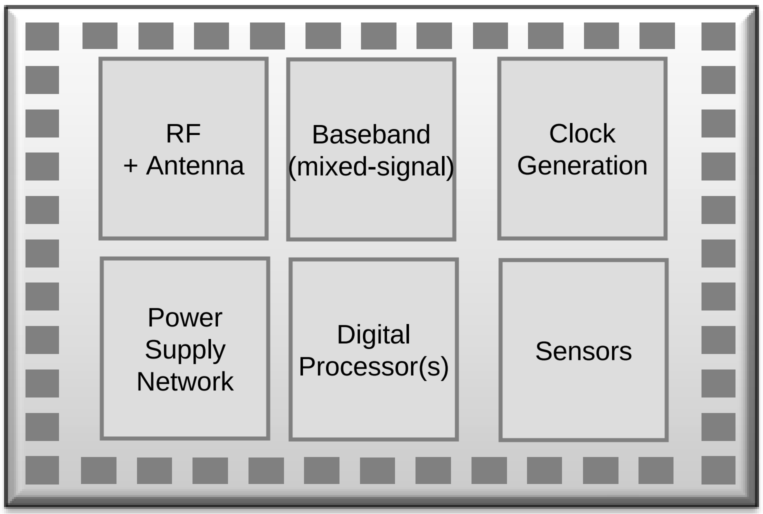
Need some major improvements if memory is to be included

Results Based on PTM (K. Cao)

Bringing it all together

0.36 ml of low-fat milk

What can we do for 3 J (= 0.72 cal!) for a year (or 0.1 μW)?



Today – 90 nm CMOS

- Transmit 950 bits/sec
- Perform 10 million adds/sec
- Perform 0.25 millon 6bit A/D conversions/sec
- Store 300 bits

Computation is cheap, sending data expensive

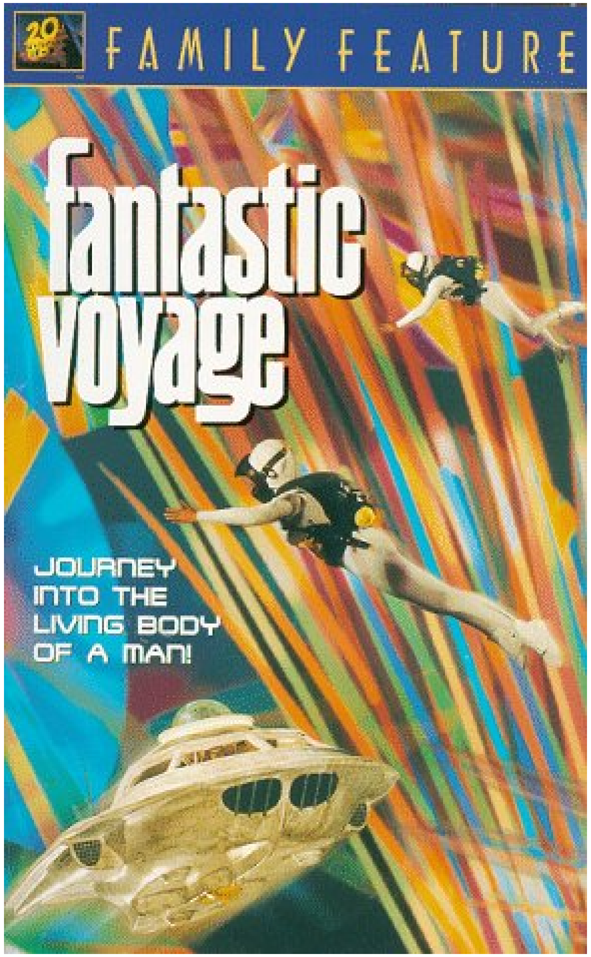
What to expect at 22 nm?

- Transmit 5000 bits/sec
- Perform 30 million adds/sec (unless we get a lot closer to energy limits)
- Perform 1 millon 6bit A/D conversions/sec
- Store 80 bits

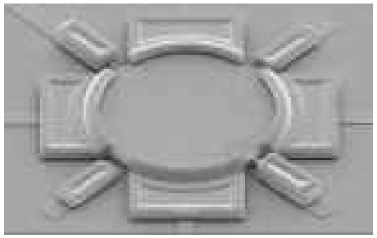
Communication becoming cheaper with respect to computation. Analog becomes more attractive.

Summary

- **Microscopic wireless may even work …**
  - There is still plenty of room at the bottom
- **However, innovative work and new ideas needed for virtually every aspect of the node**
  - Energy (!!!) and energy storage
  - Small-footprint antenna's and antenna-radio co-design
    - Merging power transmission with EFFICIENT high data rate commununication
  - Pushing the frontiers of low voltage ultra-low power radios
    - "Uncertainty"-insensitive wireless front-ends ([Pletcher 08: A Receiver with uncertain IF)
  - Mixed signal and digital processing in the millivolt regime
  - Memory????
  - What about purely passive radios, mechanical computing, and "relay neurons"?
- **While biomedical applications are a clear target, microscopic wireless is valuable for a whole slew of other applications**

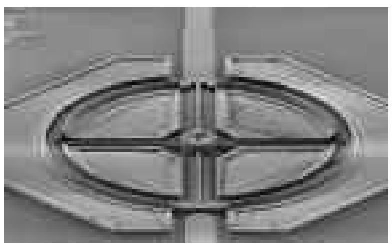


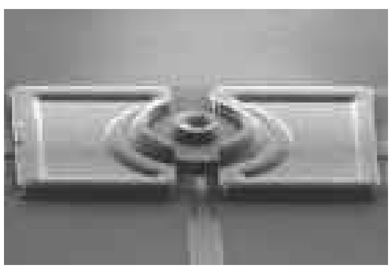
Analog/RF Processing using Nano-Mechanical Components?



60 MHz
Q = 48,000

1.2 GHz
Q = 14,600



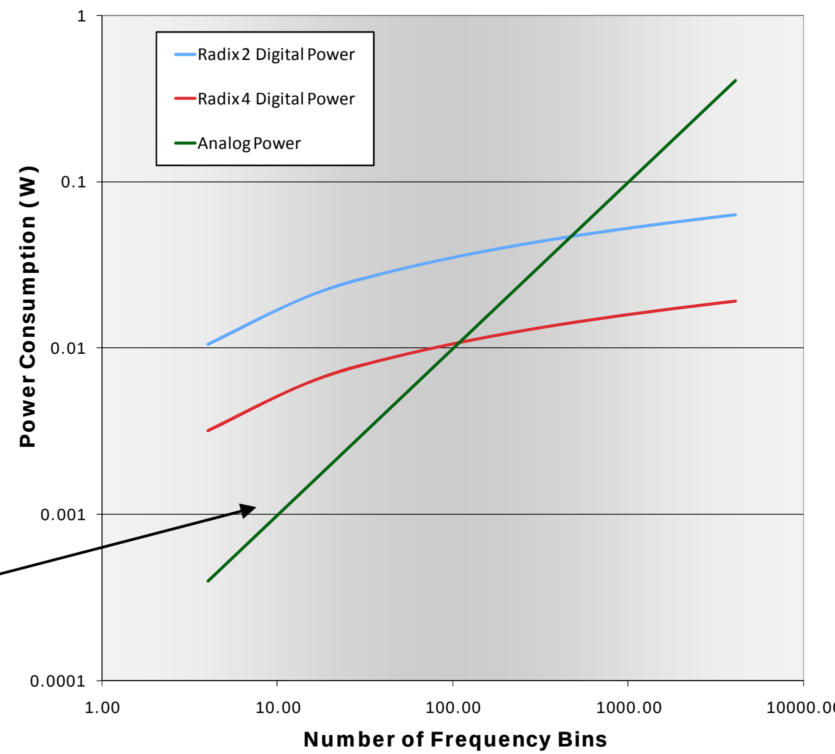


1.5 GHz
Q = 11,555

How about a NEMS spectrum analyzer?

$1mm^2$ = roughly 2000 resonators
Assume 100 μW / analog channel

Spectrum analysis @ 1 GHz with N bins



Mechanical-Analog wins for low resolutions

Keep an eye open for disruptive technologies!

Fresh from the press

NANO LETTERS

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Nanotube Radio

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