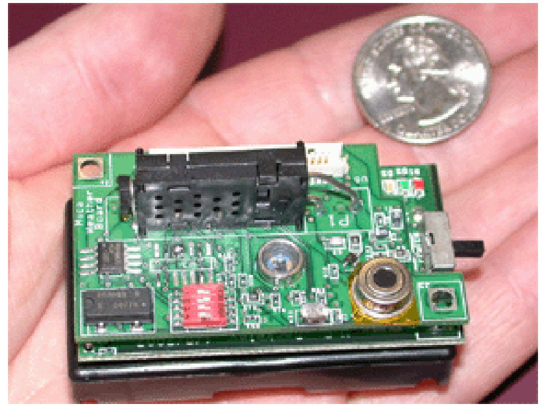
Hardware

Sensor Networks

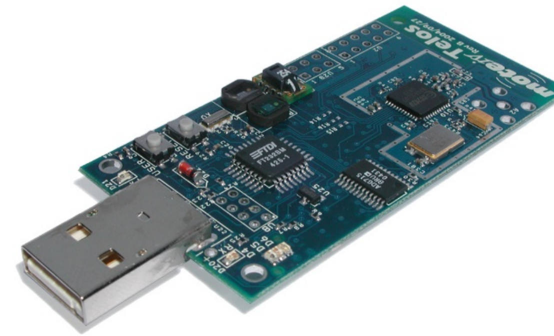
Prof. Dr. Kay Römer

Motes

Rene (1999)

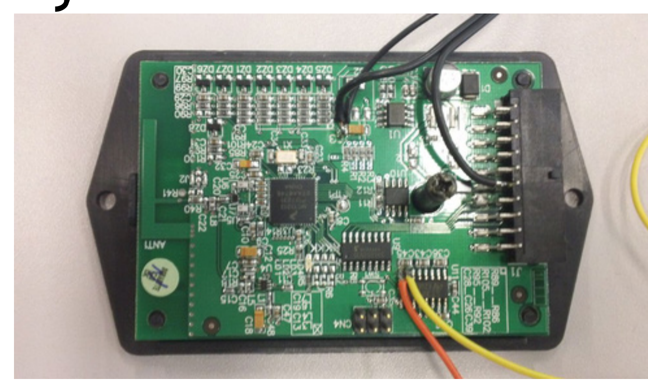


Mica (2001)



Telos (2004)

- Originally developed at UC Berkeley
  - Numerous versions: Rene, MICA, MICADot, MICAz, Telos, ...
- Other mote platforms
  - BTnode, Eyes nodes, MANTIS, XYZ, Scatterweb, OpenWSN, ...



OpenWSN (2014)

Motes: Components

- Microcontroller
  - CPU including RAM (1-10 KB) and I/O
- Communications
  - 10-500 kbps, 10-1000 meters
- Sensors
- Energy supply
  - Battery, harvesting (light, vibrations, …)
  - Power stabilization
- Additional memory
  - RAM (10-100 KB), Flash (100-1000 KB)
- Real-time clock

Component Selection

- Many different variants for each component
- Criteria for component selection
  - Lifetime (energy consumption)
  - Performance
  - Robustness
  - Size
  - Costs
- Strongly application-dependent

Processor

- Alternatives
  - Microcontroller
    - Integrated CPU, program memory, RAM, I/O, ADC
  - DSP
    - Signal processing, typically as co-processor
  - FPGA
    - Reconfigurable logic, typically as co-processor
  - ASIC
    - Only high-volume products, rarely used
- Examples
  - Texas Instruments MSP430
    - 16-bit RISC core, up to 8 MHz, up to 16 KB RAM, multiple ADC
  - Atmel ATMega 128
    - 8-bit RISC core, up to 16 MHz, up to 16 KB RAM, multiple ADC

Communication

- Medium
  - **Radio**, light, acoustics
- Properties
  - Frequency band?
  - Narrow / wide / ultra wide band?
  - Multiple channels?
  - Data rate?
  - Range?
  - Interface: bit, byte, packet?
  - Received signal strength indicator?
- Energy
  - Energy consumption for sending/receiving/listening?
  - Time and energy required for state changes?
  - Controllable transmit power?

Example Radios

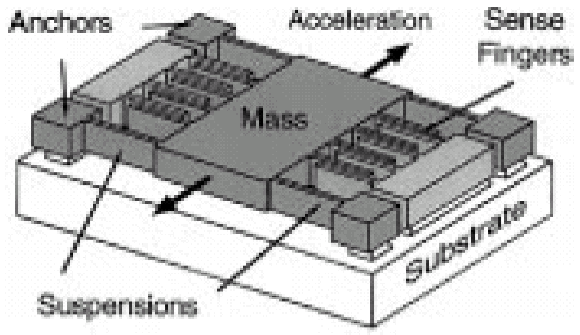
- RFM TR1000
  - Frequency: 916 / 868 MHz
  - Bandwidth: up to 115,2 kbps (in practice: 19.2 kbps)
  - Receive / transmit power consumption: 12 / 36 mW
  - Range: 10 – 20 m
  - Interface: bits
- Chipcon / Texas Instruments CC 1000
  - Frequency: 300 - 1000 MHz, programmable in 250 Hz steps
  - Bandwidth: up to 76 kbps
  - Receive / transmit power consumption: 29 / 42 mW
  - Range: 10 – 100 m
  - Interface: bytes
- Chipcon / Texas Instruments CC 2420
  - IEEE 802.15.4 ("Zigbee")
  - Frequency: 2.4 GHz and others
  - Bandwidth: up to 250 kbps
  - Receive / transmit power consumption: 38 / 35 mW
  - Range: 50 – 125 m
  - Interface: packets

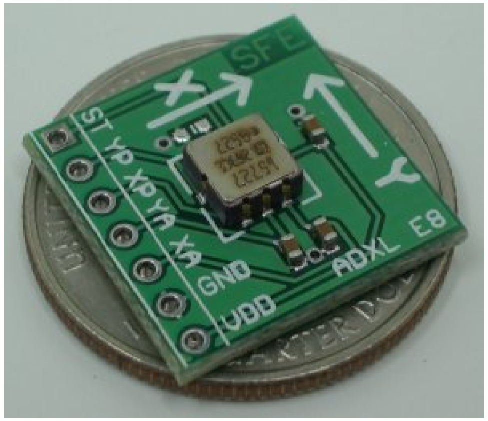
Sensors

- Categories
  - Passive vs. active
  - Directional vs. omnidirectional
- Examples
  - Passive, omnidirectional
    - Temperature, microphone, humidity, …
    - Chemical substances, gases (high energy consumption)
  - Passive, directional
    - Light, movement detector, camera
  - Active, directional
    - Radar, laser range finder
- Further properties
  - Analog vs. digital
  - Calibrated vs. uncalibrated

Example: Acceleration

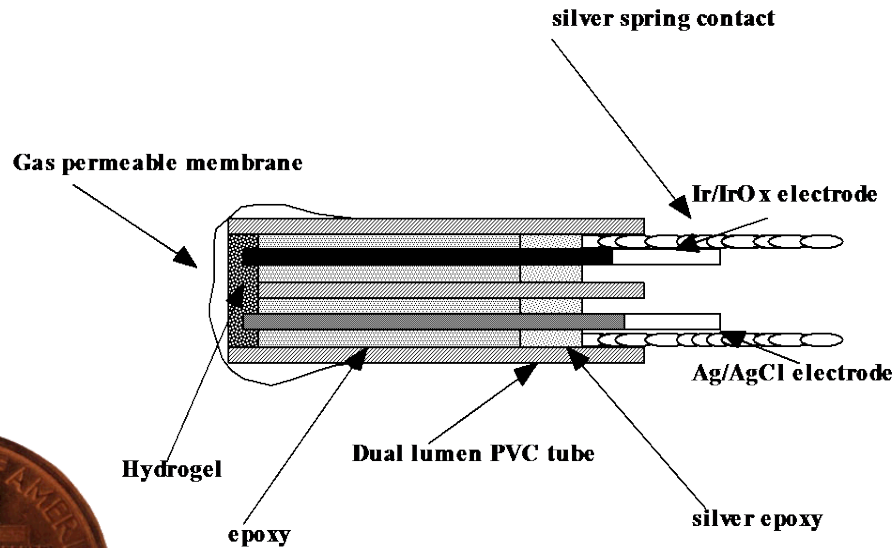
- Mass suspended on springs
  - Displacement ~ acceleration
  - One axis per mass
- Measurement of displacement
  - Piezo electric
  - Capacitive

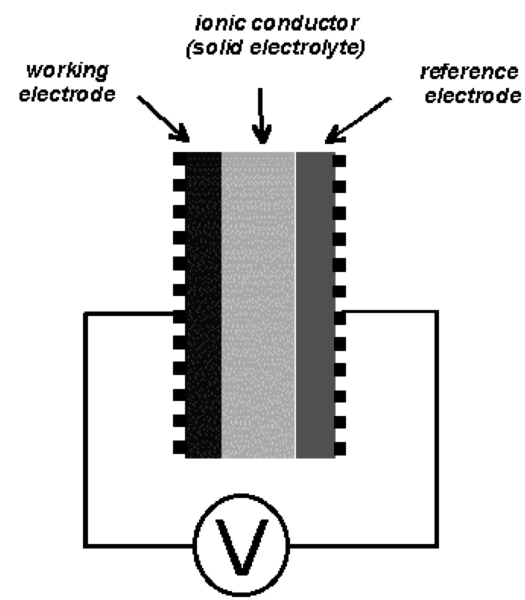




Example: CO_2

- Solution of $C0_2$ in water releases ions
  - Change of conductivity
  - Measurement of changes of electric potential between two electrodes





Energy Supply

- Options
  - Primary battery
  - Secondary battery
  - Goldcaps, supercaps: capacitors with very high capacity (1-1000 F)
  - Energy harvesting
  - Hybrid approaches

- Requirements on primary / secondary batteries
  - Low self discharge
  - Recharge parameters (charging time, number of charging cycles)
    - Relevant when used with energy harvesting
  - Recovery properties
  - Voltage stability under load and during discharge
    - Avoid voltage stabilization
    - Charge state estimation

Energy

- 1 J = 1 Nm = 1 kg m^2 / s^2
- 1 J = 1 Ws
- 1 cal ~ 4.2 J
  - Energy to heat 1 g water by 1 Kelvin

James Prescott Joule 1818 - 1889

Energy Density

Energy stored in a volume (Joule per cm^3):

Primary batteries			
Chemistry	Zinc-air	Lithium	Alkaline
Energy (J/cm^3)	3780	2880	1200
Secondary batteries			
Chemistry	Lithium	NiMH	NiCd
Energy (J/cm^3)	1080	860	650

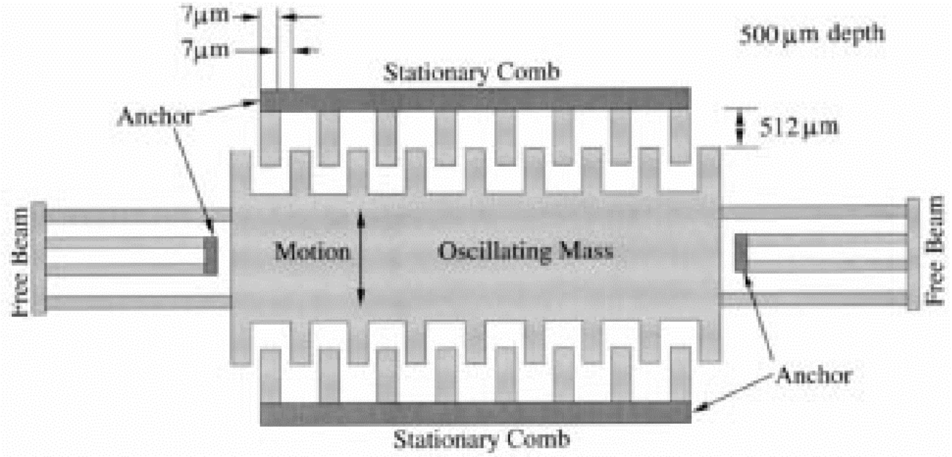
- Supercaps: up to about 17 J/cm^3
  - $E = \frac{1}{2} C U^2$

Energy Harvesting

- Convert other forms of energy into electrical energy
- Examples
  - (Fuel cells: 10 – 100 mW / cm^2)
  - Solar cells: 10 μW/cm^2 - 15 mW/cm^2
  - Temperature gradients: 80 μ W/cm^2 @ 1 V at 5K gradient
  - Vibrations: 0.1 - 10000 μ W/cm^3
  - Pressure (piezo-electric): 330 μ W/cm^2 (shoe)
- Other candidates
  - Air/water flow (MEMS turbines): 0.1-10 W/cm^3 expected
  - Radio nuclide battery: up to 150 W/g, but only 3-8% efficiency (?)

Example: Vibrations

- Different approaches, cf. accelerometer
  - Piezo electric
  - Electrostatic
  - Electromagnetic
- Example: electrostatic
  - U = Q / C ~ Q x d / A
  - Area large
    - Charge with Q
  - Area small
    - Discharge
  - Why is this effective?
    - Charge Q, distance constant, area shrinks
    - Increase of voltage



Energy Consumption

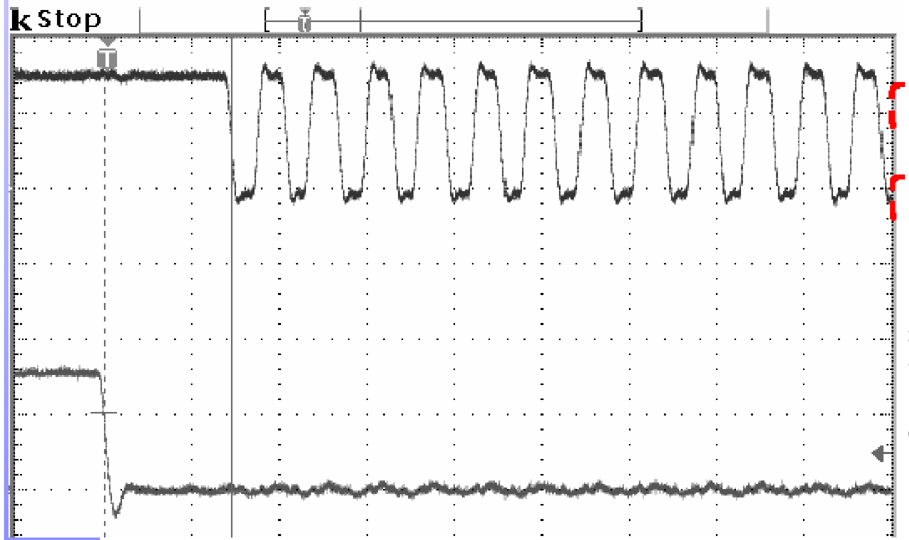
- Typical energy consumption figures (Telos mote)
  - Energy per instruction: 1 nJ (duration ~ 100ns)
  - Send one byte: 1 uJ (duration ~ 30 us)
  - Write one byte to Flash: 3 uJ (duration ~ 80 us)
- Compute vs. communicate
  - 1000 instructions ~ 1 byte transmission
  - Compute to reduce communication (data reduction)
- Expected lifetime
  - Li battery some cm^3: 10000 J
  - CPU: ~ 12 days
  - Radio: ~ 4 days
  - Flash: ~ 4 days
- Too short!

Duty Cycling

- Duty cycling
  - Long sleep phase (typically > 99%)
    - Hardware switched to low-power sleep mode
  - Quick wakeup
    - Activate all components (takes time and energy!)
  - Short wake time
    - Sense, process, send and go back to sleep
- Minimize integral over power consumption
  - Radio, processor, ...
- Achievable lifetime: years

Wakeup

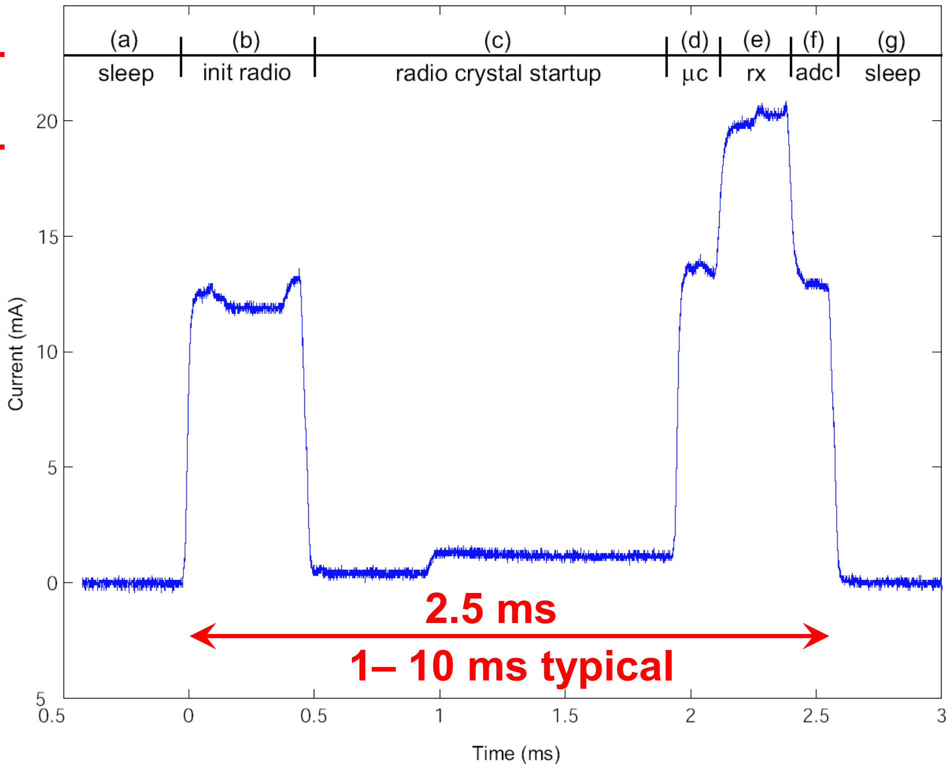
Micro controller



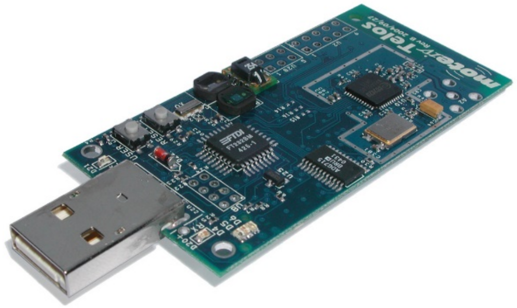
292 ns

10ns – 4ms typical

Radio

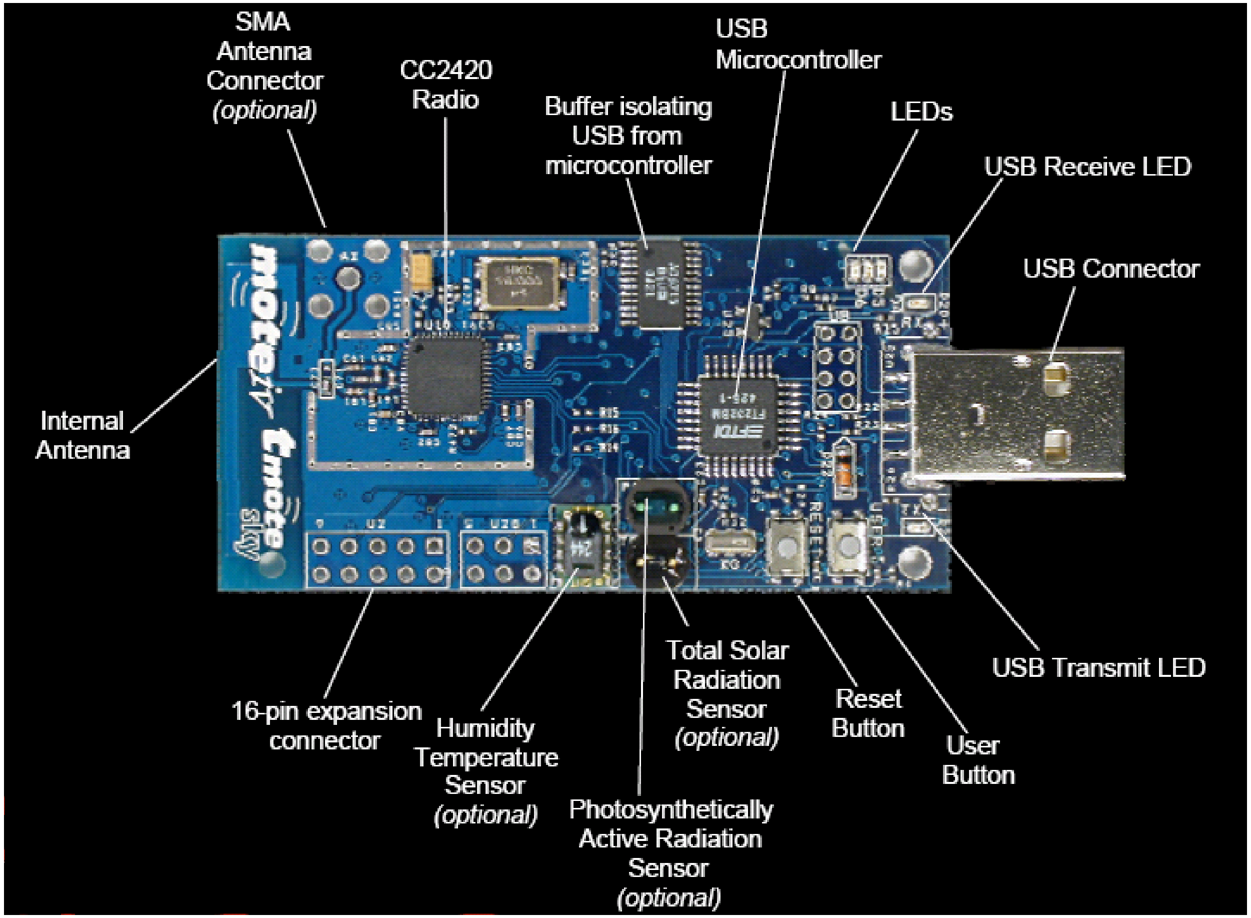


Example: Telos Tmote

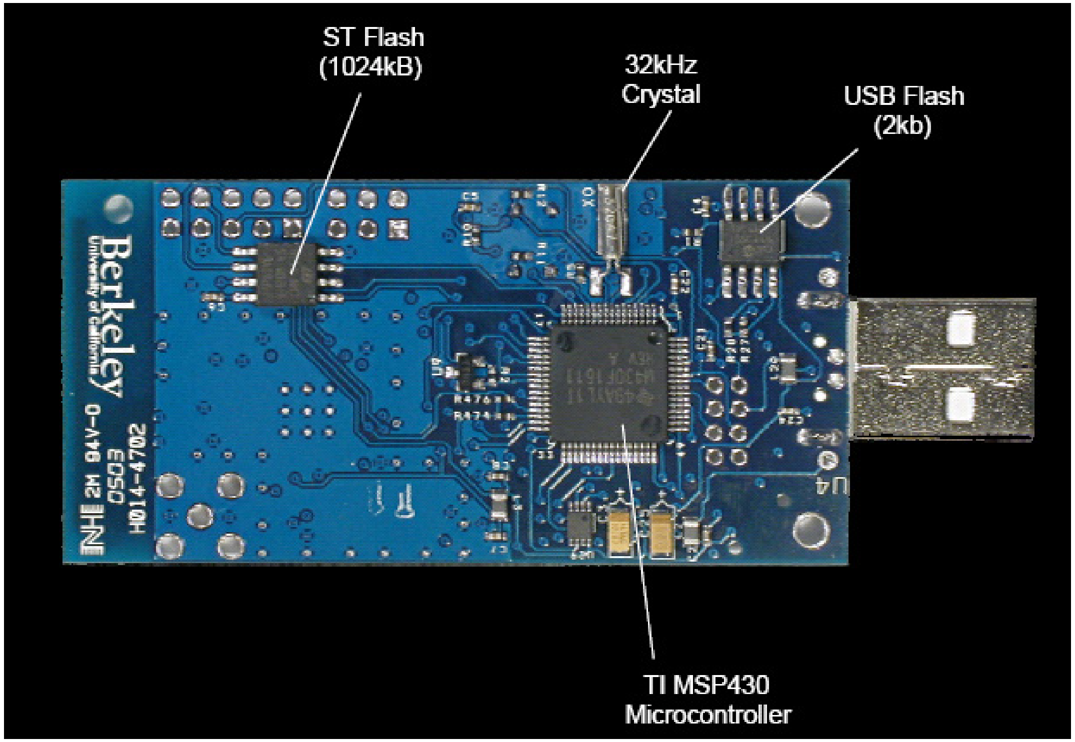


- Micro controller
  - Texas Instruments MSP 430
  - 2 KB RAM, 60 KB Flash
- Radio
  - Chipcon CC2420 (IEEE 802.15.4, „Zigbee“)
  - 250 kbps, 50-125 m
- Sensors
  - Temperature, humidity, photosynthetic active light, visible light
  - Expansion slot

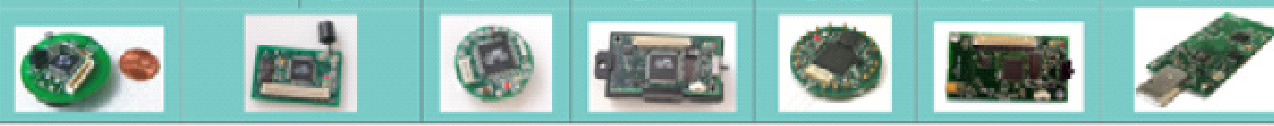
Example: Telos Tmote



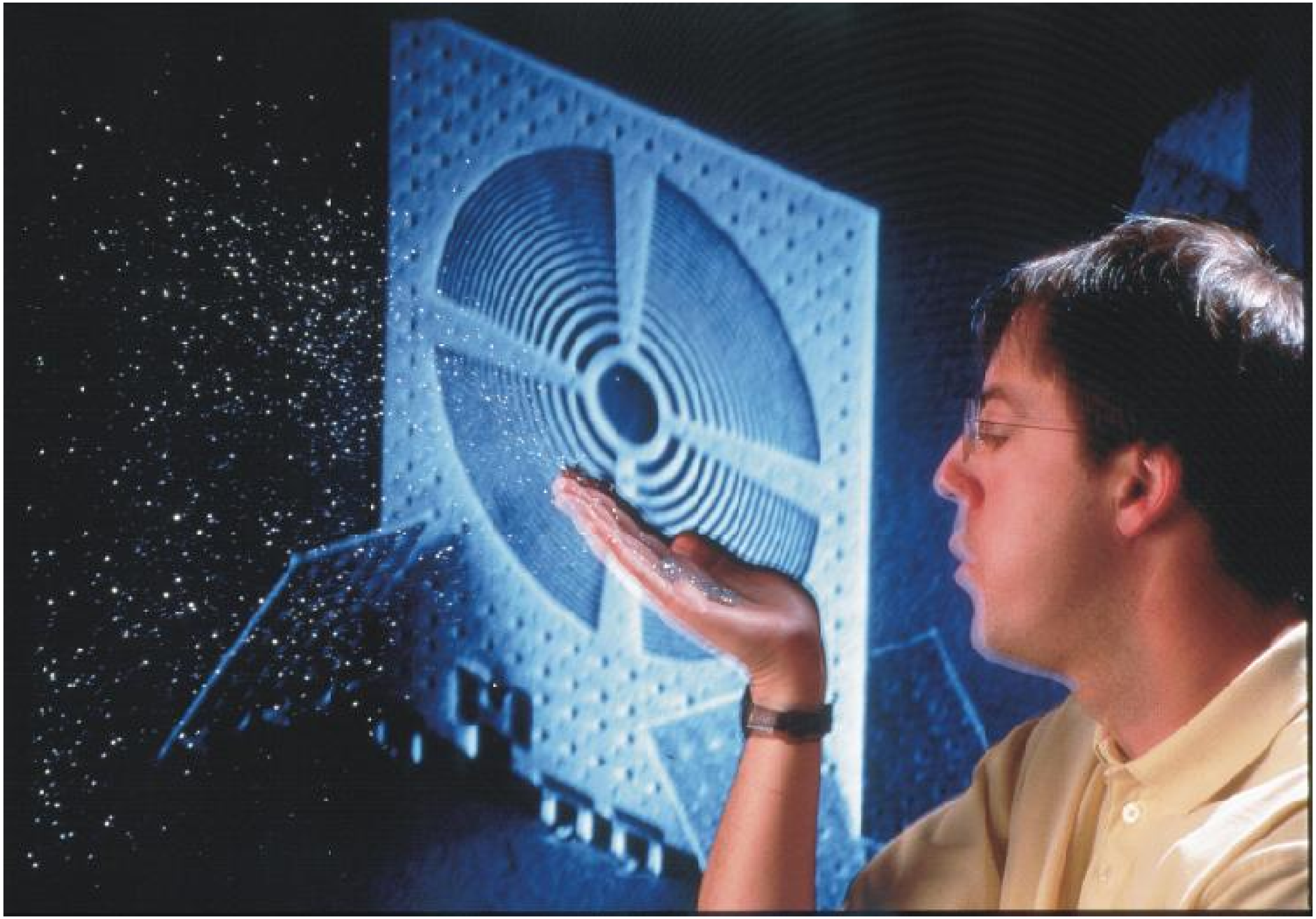
Example: Telos



Motes Compared

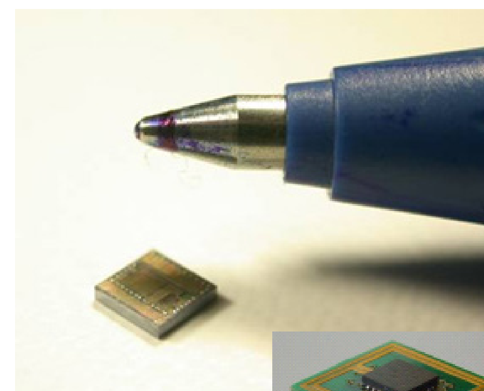
Mote Type Year	*WeC* 1998	*René* 1999	*René 2* 2000	*Dot* 2000	*Mica* 2001	*Mica2Dot* 2002	*Mica 2* 2002	*Telos* 2004
								
Microcontroller								
Type	AT90LS8535		ATmega163		ATmega103		ATmega128	TI MSP430
Program memory (KB)	8		16		128			60
RAM (KB)	0.5		1		4			2
Active Power (mW)	15		15		8		33	3
Sleep Power (μW)	45		45		75		75	6
Wakeup Time (μs)	1000		36		180		180	6
Nonvolatile storage								
Chip	24LC256				AT45DB041B			ST M24M01S
Connection type	I^2C				SPI			I^2C
Size (KB)	32				512			128
Communication								
Radio	TR1000				TR1000	CC1000		CC2420
Data rate (kbps)	10				40	38.4		250
Modulation type	OOK				ASK	FSK		O-QPSK
Receive Power (mW)	9				12	29		38
Transmit Power at 0dBm (mW)	36				36	42		35
Power Consumption								
Minimum Operation (V)	2.7		2.7		2.7			1.8
Total Active Power (mW)	24				27	44	89	41
Programming and Sensor Interface								
Expansion	none	51-pin	51-pin	none	51-pin	19-pin	51-pin	10-pin
Communication	IEEE 1284 (programming) and RS232 (requires additional hardware)							USB
Integrated Sensors	no	no	no	yes	no	no	no	yes

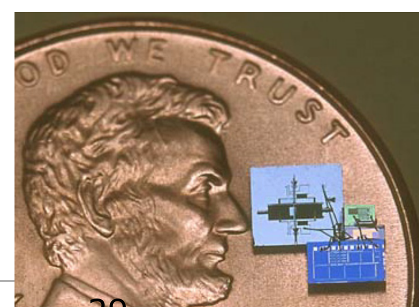
Miniaturization



Miniaturization

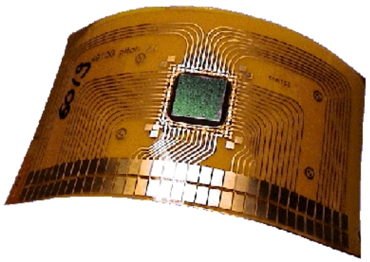
- So far: motes using commercial components
  - „COTS Dust“
- Vision „smart dust“
  - Sensor node as small as a dust grain?
- Different strategies
  - Efficient packaging
  - System on chip
  - MEMS

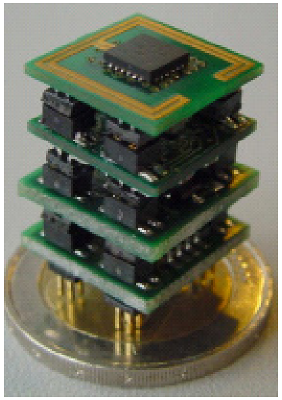


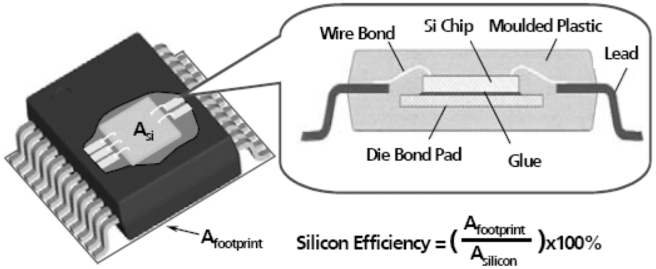


Packaging

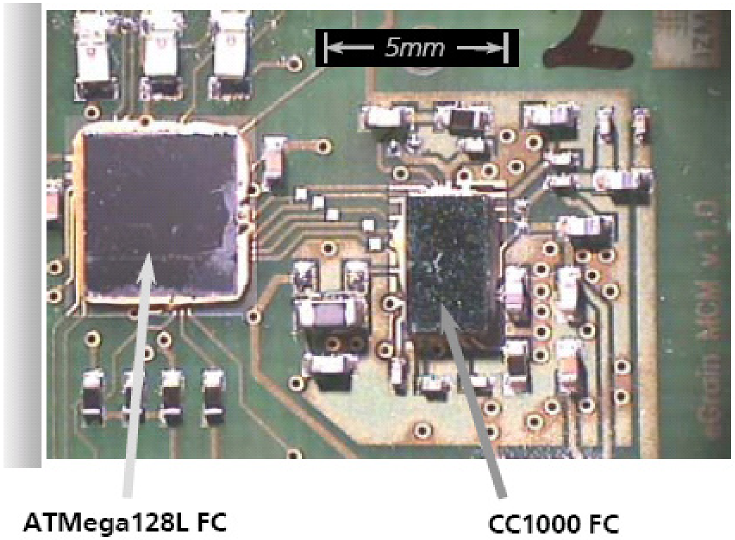
- 3D instead 2D
  - Stackable PCBs
  - Flexible PCBs
- Other chips
  - Chip area << package size
  - Multi chip module
    - „naked“ dies (Flip Chips)
    - One package for whole sensor node
    - Reduction by factor 2.5 - 5







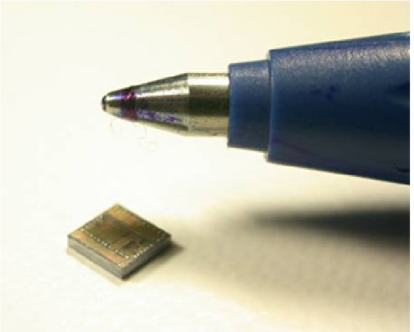
Multi Chip Module

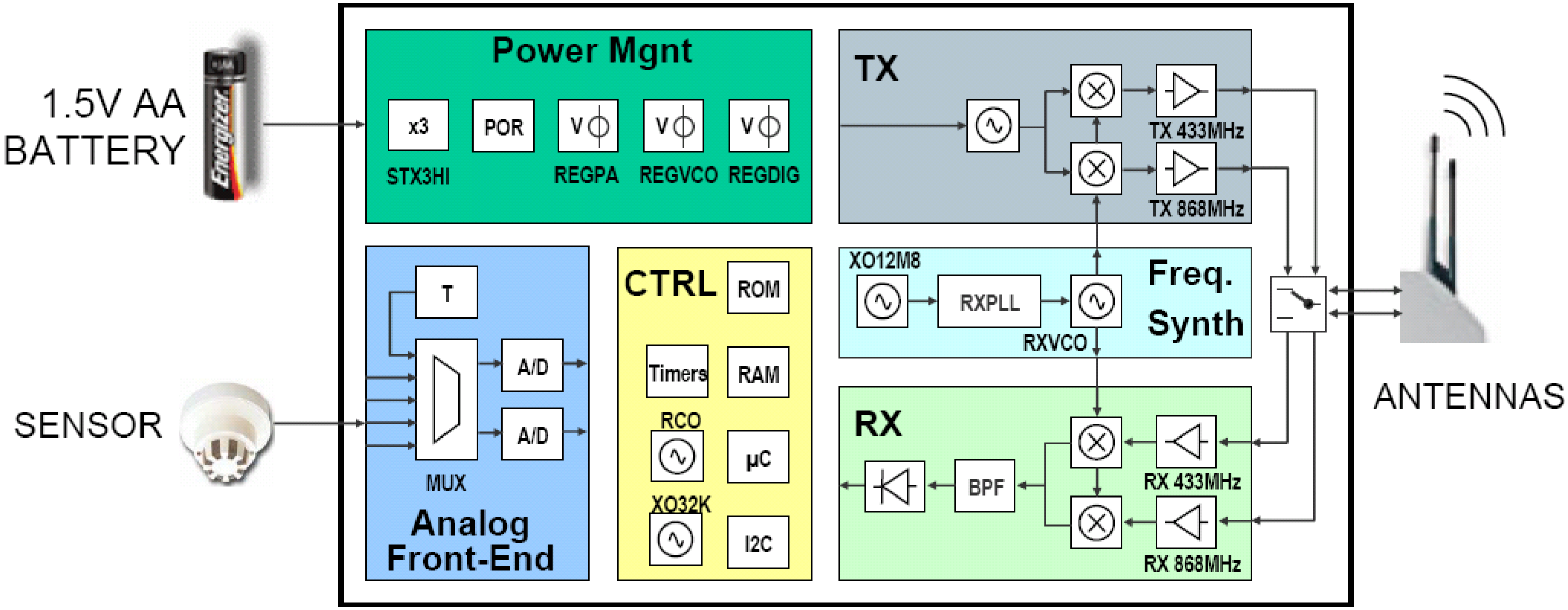


Version	*Components square [mm²]*						*Total Functional Square [mm²]*	*Total Surface [mm²]*
	Sensors	*Passives (RLC)*	*IC*	*LED*	*Quartz*	*Others*		
SMD	19,10	60,64	333,79	43,20	19,80	292,16	768,69	$3x52^2$=4056
MCM	15,51	30,92	22,01	14,28	10,00	155,76	248,48	$2x40^2$=1600
Reduction Factor	1,2	2,0	15,2	3,0	2,0	1,9	3,1	2,5

System on Chip

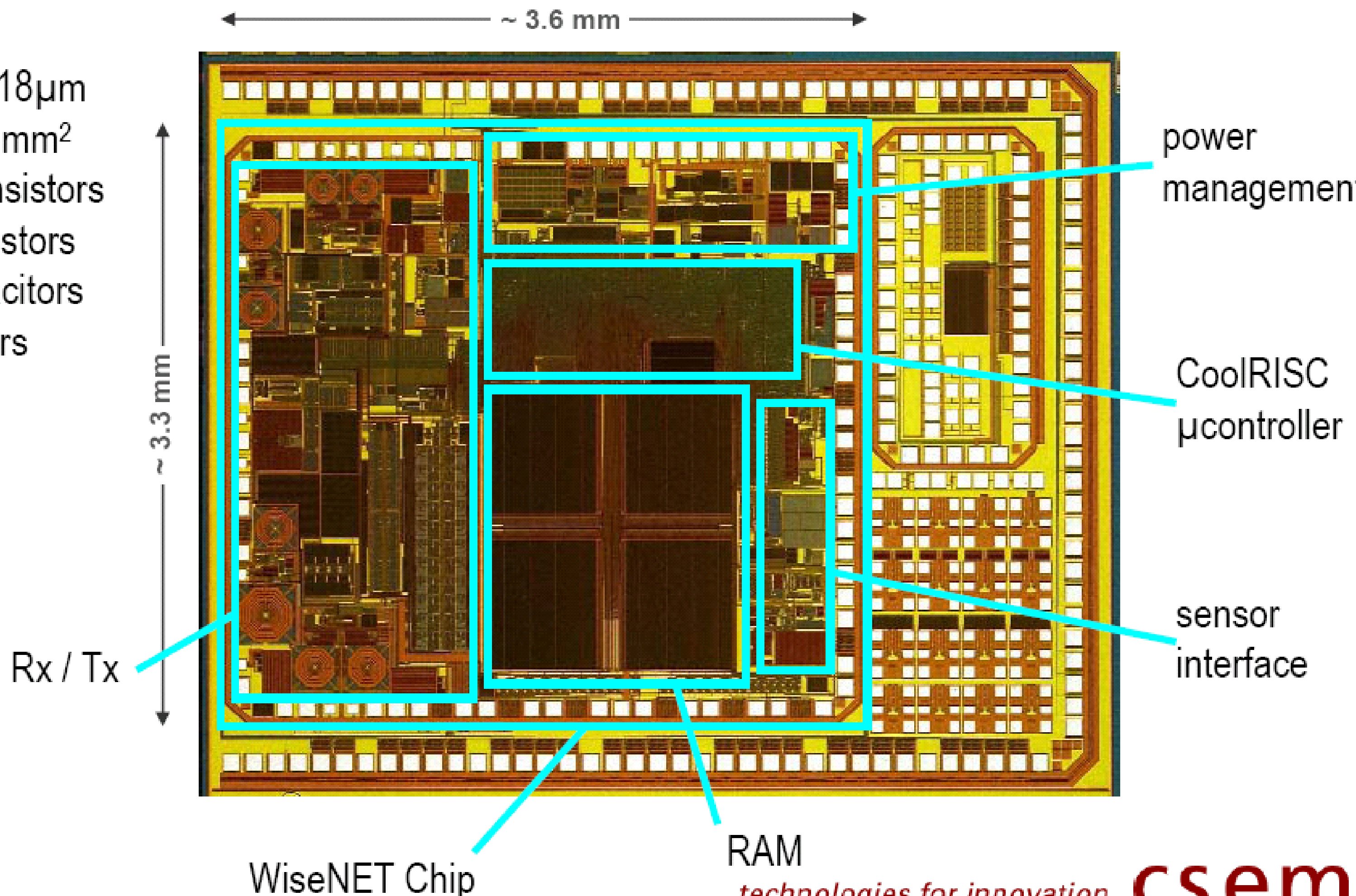
- Almost all electronics on a single chip
  - Minimal external components





WiseNet SoC

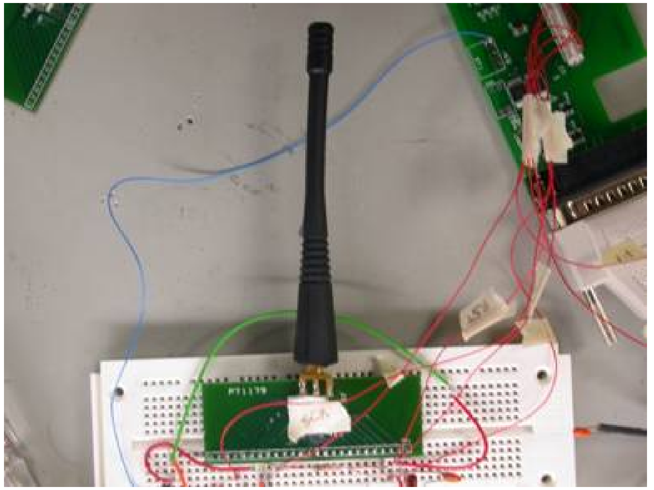
TSMC 0.18µm
3.6 x 3.3 mm^2
1.7M transistors
1906 resistors
341 capacitors
8 inductors



technologies for innovation csem

SoC = Smart Dust?

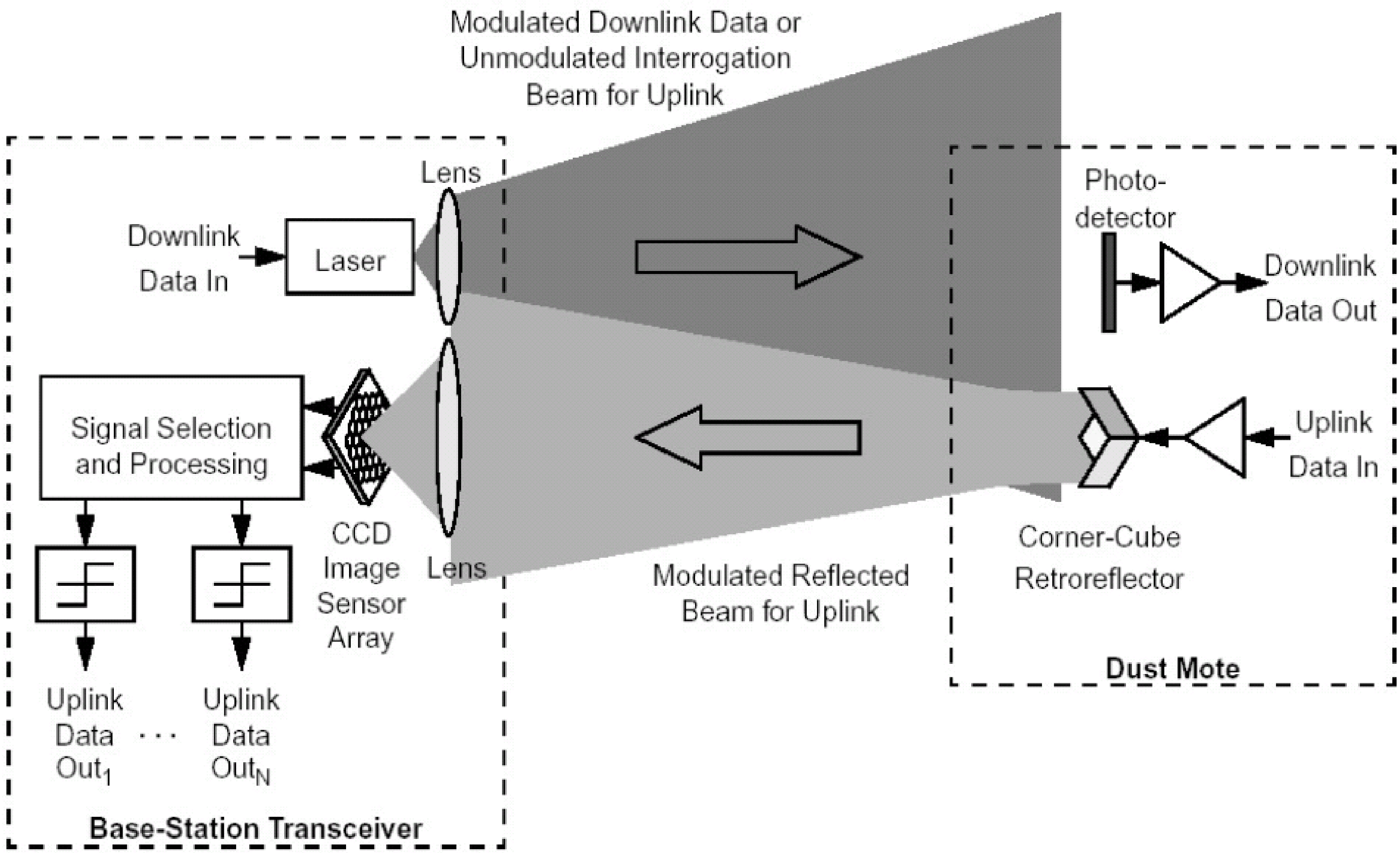
- Antennas
  - Mono pole: length $\lambda/4$
  - At 1 GHz -> 10 cm
  - Higher frequencies -> more energy
- Batteries
  - Energy consumption does not scale with size!
- Main challenge: radio
  - Complex signal processing
  - Relatively high transmit power



Alternatives to Radio?

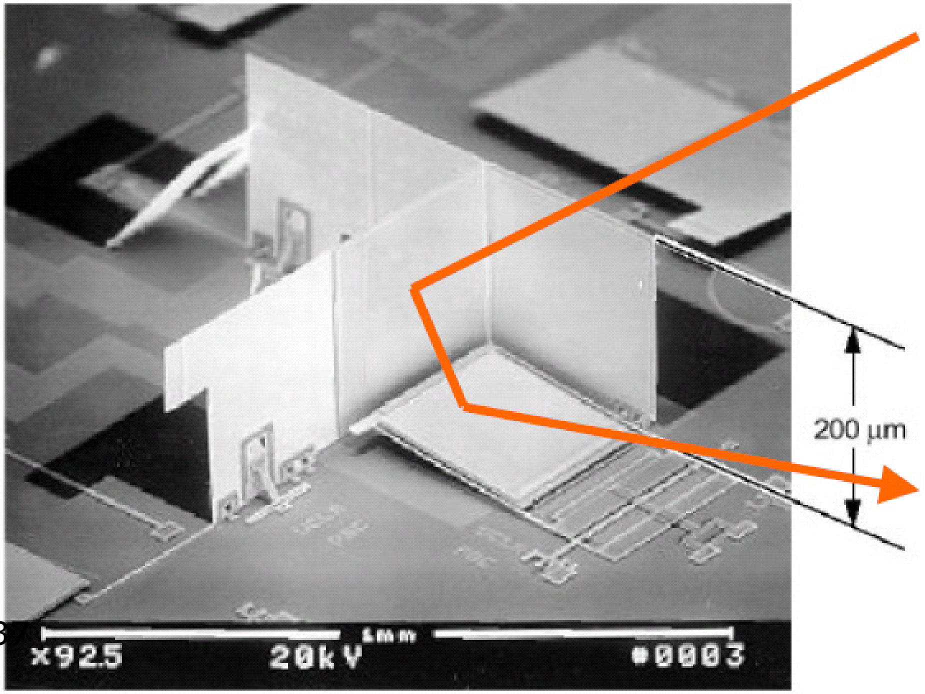
- Laser
  - Focus: large range with small transmit power
    - Several km at 5 mW transmit power
  - Optical receiver simple: low energy consumption
  - Optical receiver („antenna“) very small
    - Photo diode integrated into SoC
- Passive laser communication
  - Base station to/from sensor node

Passive Laser Communication

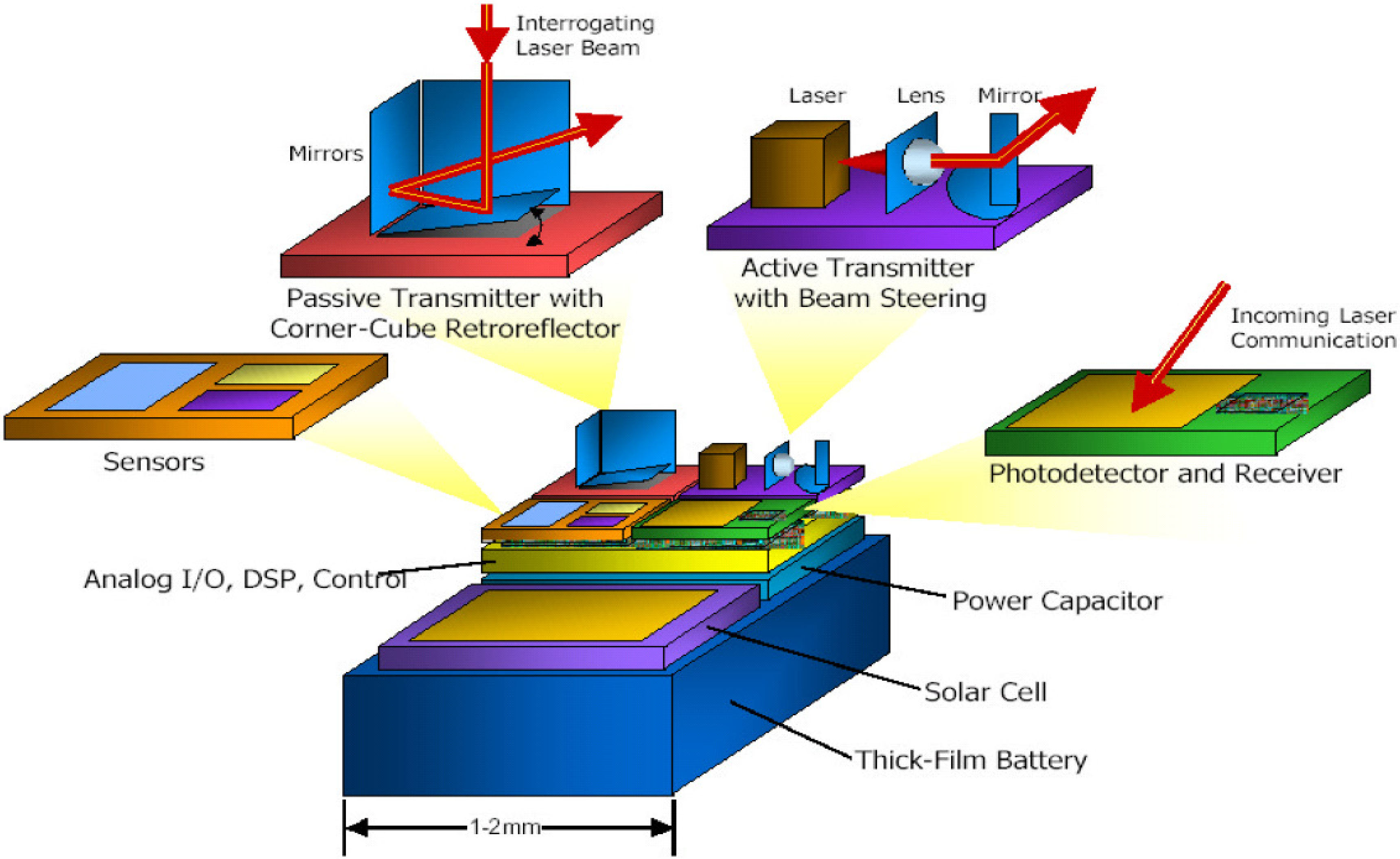


Modulation + Reflection

- Corner Cube Retroreflector (CCR)
  - Reflex reflector: light reflected to source
  - Third mirror can be deflected electrostatically
  - ~ 1-10 kbps
  - ~ 150 m at 5 mW

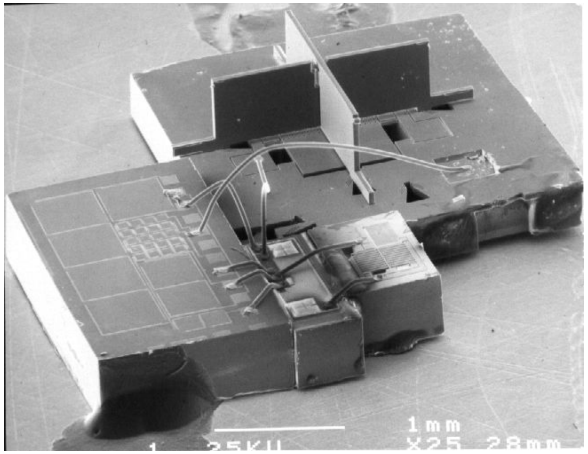


Smart Dust: Architecture



Smart Dust Prototype

- Smart Dust Prototype
  - Volume: 16mm^3
  - Transmit energy: 16 pJ/bit
  - Receive energy: 69 pJ/bit
  - Energy supply
    - Battery (1 J) + capacitor (1 mJ) + solar cell



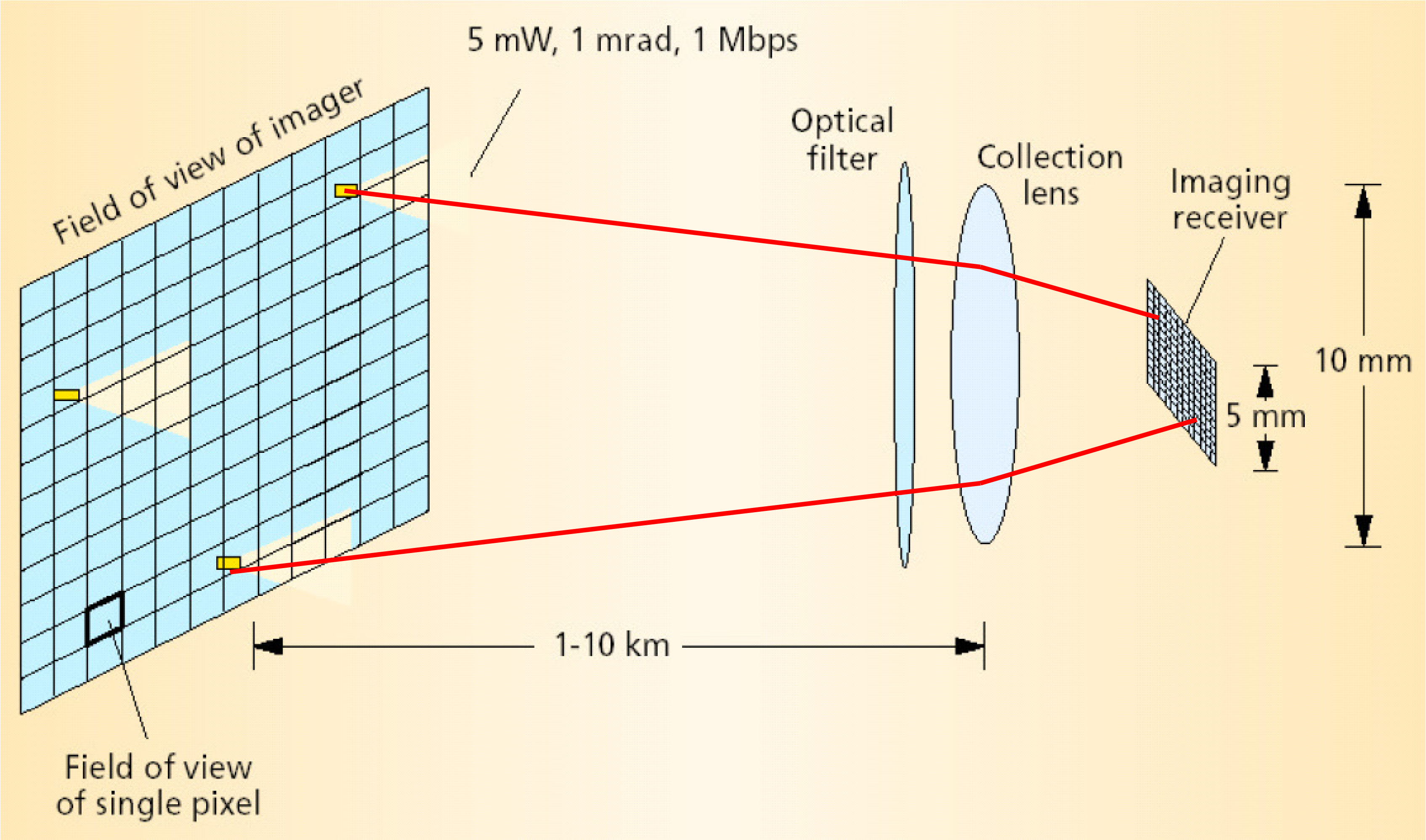
- Cf. radio-based mote
  - Volume: some cm^3
  - Transmit energy (min): > 1 nJ/bit
  - Transmit energy (real): > 100 nJ/bit

Base Station

- Transmit
  - Defocussed laser
  - Raster scanning (cf. tv tube)

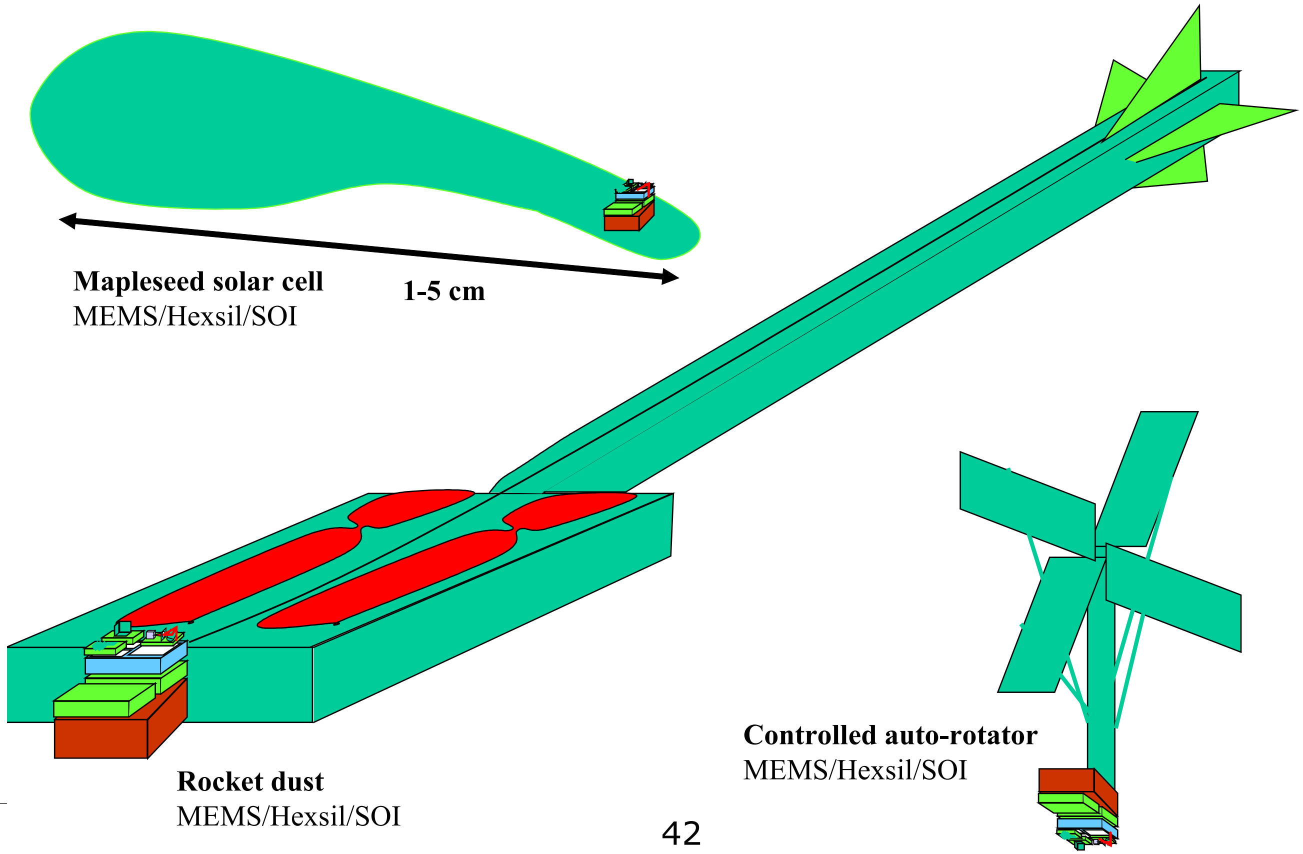
- Receive
  - Video camera with high frame rate
  - Simultaneous reception from many nodes
    - One node per pixel
    - Space division multiplexing

Base Station

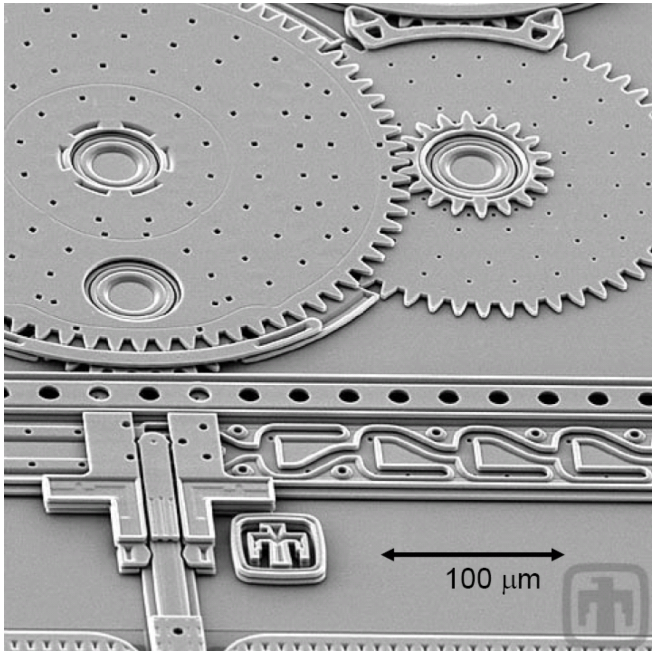


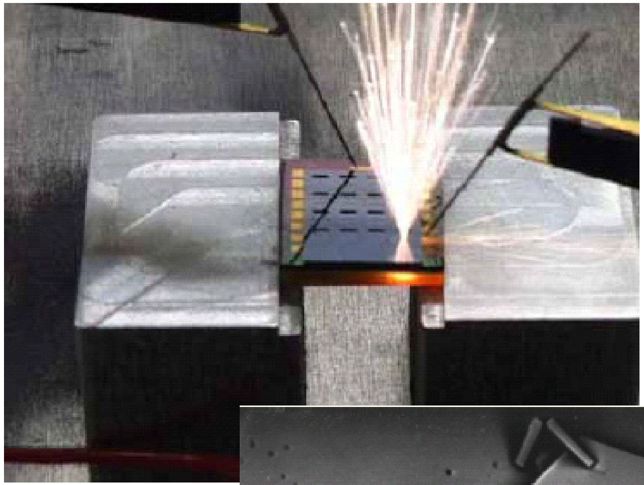
Mobile Smart Dust?

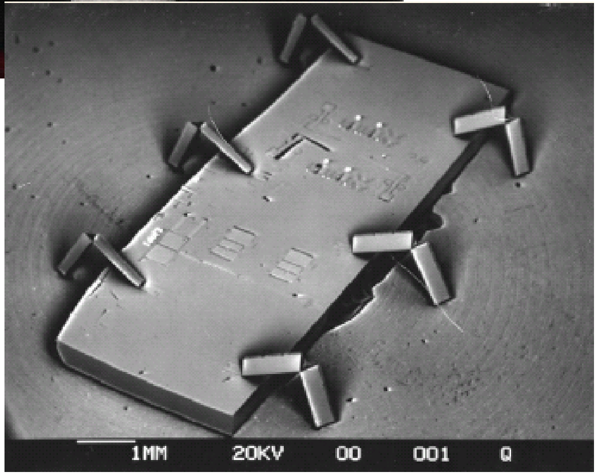
- Flying, crawling
- MEMS (cf. CCR) for mobility

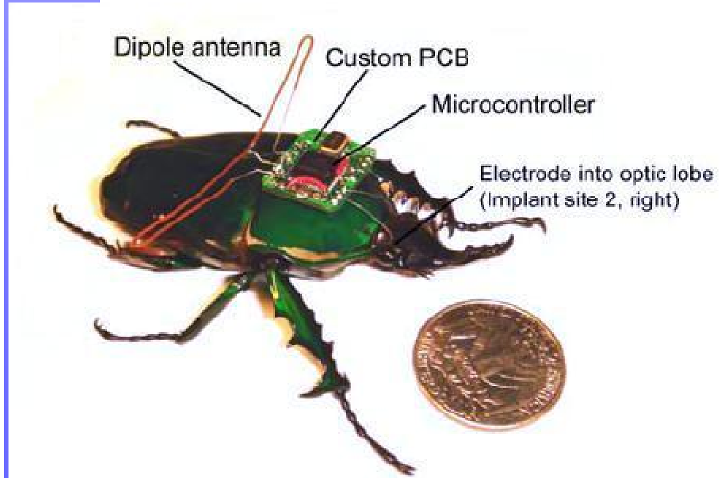


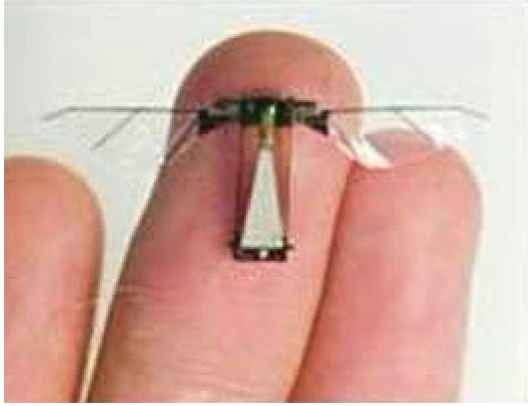
Mobile Smart Dust?









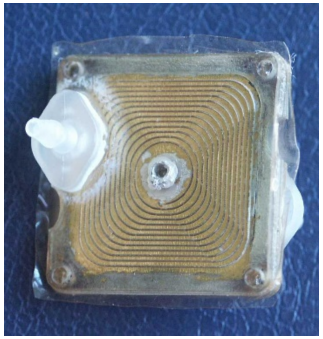


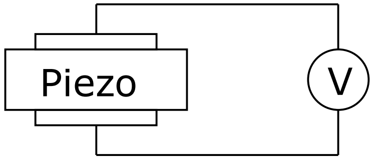
Smart Dust: Holy Grail?

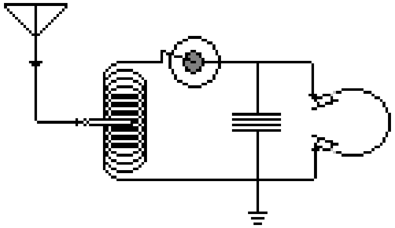
- So far only prototypes
- Free line of sight
- Orientation of nodes important
- No direct communication among nodes
- Many applications don’t need dust size

Future?

- Moore's law: Number of transistors per area doubles every 18 months
  - Will continue for another 10+ years
    - Intel's 3D transistor
  - Implies
    - Cost reduction
    - Lower energy consumption
- New technologies
  - New energy sources
    - Tiny fuel cells
  - More efficient radios
    - Electro mechanical resonators instead of complex signal processing
    - FBAR: Film Bulk Acoustic Resonator
    - Cf. crystal radio
    - Goal: < 100 uW







References

- Slides contain material by the following authors:
  - Joe Polastre, Chris Pister, Brett Warneke, Jason Hill, Jan Rabaey – UC Berkeley
  - Jan Beutel – ETH Zurich
  - Christian Enz – CSEM
  - Herbert Shea – EPFL
  - David Polityko – Fraunhofer IZM
  - Tom Torfs – IMEC
  - Holger Karl – Uni Paderborn
  - Marc Madou – UC Irvine