Challenges: Resources

Ubiquitous Information and Communication

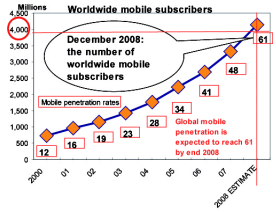
- Ubiquitous computing systems are made possible because of:
  - Advances in technology
    - processing power/storage
    - GPS, smart cards, RFID
    - social developments
- And particularly…
  - World Wide Web accessibility
  - Mobile communication popularity

World Wide Web

- People have become accustomed to web portals reducing attachment to one device.
- People use multiple devices in a single day to access info
- Web encouraged us dealing with privacy issues.

Mobile Communications

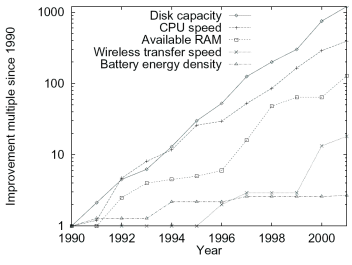
- Phones offer many capabilities and are now a commodity



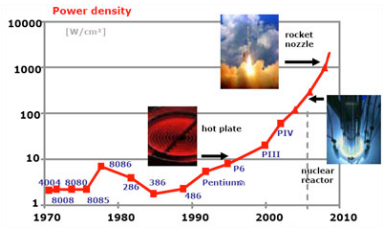
Key Technological Challenge: Energy

- ***"Power is considered as the most important constraint in embedded systems"***
  [in: L. Eggermont (ed): Embedded Systems Roadmap 2002, STW]
- **Current UMTS phones can hardly be operated for more than an hour, if data is being transmitted.**
  [from a report of the Financial Times, Germany, on an analysis by Credit Suisse First Boston; http://www.ftd.de/tm/tk/9580232.html?nv=se]

Energy

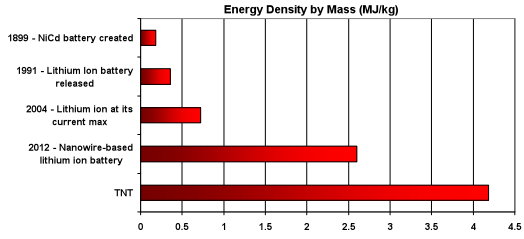


Power Density



Limits to Battery Energy Density

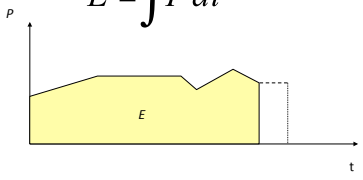
- Processing power doubles every **2 years**, but…
- Battery capacity doubles every **10 years**



Power and Energy

- In many cases, faster execution also means less energy, but the opposite may be true if power has to be increased to allow faster execution.

$$E = \int P\,dt$$

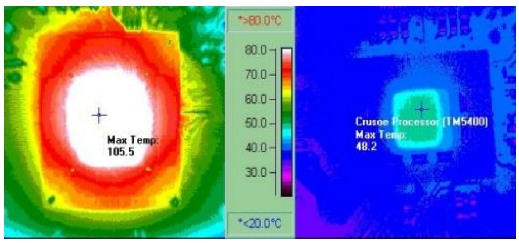


Power and Energy

- Minimizing the **power consumption** is important for
  - the design of the power supply
  - the design of voltage regulators
  - the dimensioning of interconnect
  - short term cooling
- Minimizing the **energy consumption** is important because of
  - restricted availability of energy (mobile systems)
    - limited battery capacities (only slowly improving)
    - very high costs of energy (solar panels, in space)
  - cooling
    - high costs

Energy

Pentium Crusoe

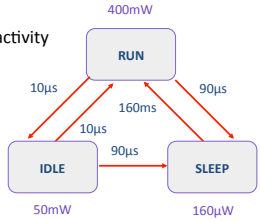


Running the same multimedia application.

As published by Transmeta [www.transmeta.com]

Dynamic Power Management

- Example: STRONGARM SA1100
  - RUN: operational
  - IDLE: a software routine may stop the CPU when not in use, while monitoring interrupts
  - SLEEP: Shutdown of on-chip activity



Dynamic Voltage Scaling

$P = \alpha\ C_L V_{dd}^2\ f$ with

α : switching activity

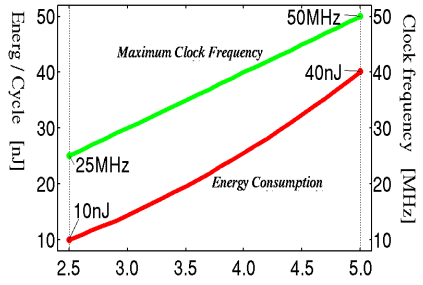
C_L : load capacitance

V_{dd} : supply voltage

f : clock frequency

☞ *Decreasing V_{dd} reduces P quadratically*,
while the run-time of algorithms is only linearly increased
(ignoring the effects of the memory system).

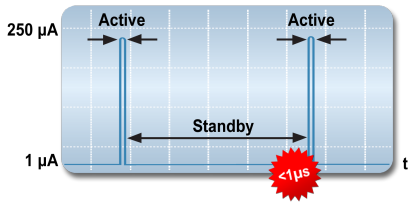
Dynamic Voltage Scaling



Ultra Low-Power Processing

- MSP430 is ideal for energy harvesting
- Low standby current <1uA
- Low active current 160uA/MHz
- Instant off and quick wakeup time <1us
- Integrated low power ADC for precision measurements (great for sensors)
- Low operating voltage 1.8V to 3.6V
- Low pin leakage <50nA
- Lower power, highly integrated new products: 5xx-based RF SoC
- Efficient 16-bit architecture with high code density and processing power

Ultra Low-Power Activity Profile



- Extended *Ultra-Low-Power* standby mode
- Minimum active duty cycle
- Interrupt driven performance on-demand

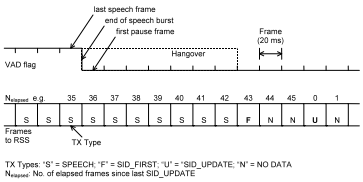
Radio

Factors affecting the power consumption characteristics of a radio:
- modulation scheme used
- data rate
- transmit power (determined by the transmission distance)
- operational duty cycle

- In general, radios can operate in four distinct modes of operation: Transmit, Receive, Idle, and Sleep.
- An important observation in the case of most radios is that operating in Idle mode results in significantly high power consumption, almost equal to the power consumed in the Receive mode.
- When the radio's operating mode changes, the transient activity in the radio electronics causes a significant amount of power dissipation (and a delay during which the radio may not be available).

Example: GSM

- Discontinuous Transmission
  - Allows the radio transmitter to be switched off most of the time during speech pauses
  - Specified in GSM, WCDMA and cdma2000 standards



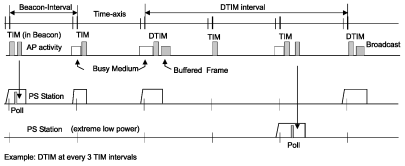
TX Types: 'S' = SPEECH; 'F' = SID_FIRST; 'U' = 'SID_UPDATE; 'N' = NO DATA
$N_{elapsed}$: No. of elapsed frames since last SID_UPDATE

Example: IEEE 802.11

- IEEE 802.11 (WLAN for unlicensed bands)
  - Two modes: Infrastructure (BSS), ad-hoc (IBSS)
- Power Management
  - Sleeping without missing any incoming frame
    - Without power management, a STA always senses medium
    - Lots of power consumption for channel sensing
  - Periodic sleep, frame buffering
    - Power management allows STAs to enter doze state as much as possible without losing incoming data
    - Active mode – always awake state
    - Power Save (PS) mode – switch between awake and doze states

PS Mode of 802.11

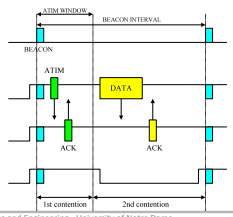
- Periodic sleeping
  - Switch between active and PS mode is informed via a successful frame transmission with a Power Mgmt message
  - In BSS, AP buffers downlink frames, and announces them via beacon frames (in TIM field)
  - In IBSS, each STA buffers frames, and announces them via ATIM frames
  - Power-saving STAs wake up periodically



Example: DTIM at every 3 TIM intervals

802.11 Ad Hoc Mode

- ATIM window
  - STAs are always awake during ATIM window
  - If STAs know, during ATIM window, that they have buffered data to transmit or receive, they are awake for all the Beacon interval



Energy Is Everywhere

Light

Radio frequency

Motion and vibration

Heat

Energy Harvesting

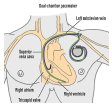
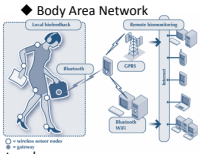
- *Energy harvesting* is the process by which energy is *captured* and *stored*
- This term typically refers to small autonomous devices – micro energy harvesting
- A variety of sources exist for harvesting energy
  - solar power – salinity gradients
  - thermal energy – kinetic energy
  - wind energy – radio frequency

Not a New Idea

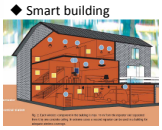
Energy Harvesting Applications

Low data rate, low duty cycle, ultra-low power

- Medical and Health monitoring
- Body Area Network
- Structure Health monitoring
- Wireless Sensor Networks
- Smart building





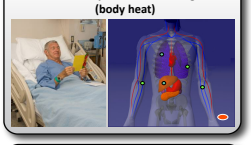
Tradeoffs

- **Advantages**
  - Mobile: no power wires
  - Easier installation
  - Lower maintenance
  - Environmentally friendly
  - Higher uptime
- **Disadvantages**
  - Dependent on availability of harvestable energy source
  - Strict power budget
  - Upfront cost may be higher
  - Less mature technology

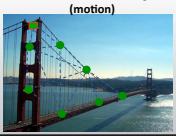
Permanently Powered Sensors

- Remote patient monitoring
- Harmful agents detection
- Efficient office energy control
- Surveillance and security
- Detecting and tracking enemy troop movement
- Vineyard or other agricultural management
- Home automation
- Implantable sensors
- Long range asset tracking
- Aircraft fatigue supervision

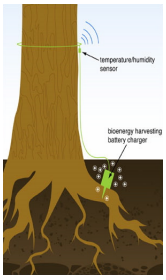
Remote patient monitoring (body heat)



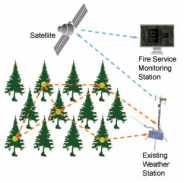
Structural monitoring (motion)



Tree Energy Harvesting



A new MIT tree sensor system taps into trees as a self-sustaining power supply. Each sensor is equipped with an off-the-shelf battery that can be slowly recharged using electricity generated by the tree.

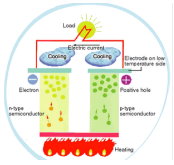


The sensor system produces enough electricity to allow the trees' temperature and humidity sensors to regularly and wirelessly transmit signals. Each signal hops from one sensor to another, until it reaches an existing weather station that beams the data by satellite to a forestry command center.

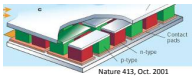
Energy Harvesting Sources

Energy Source	Characteristics	Efficiency	Harvested Power
Light	Outdoor Indoor	10~24%	100 mW/cm² 100 μW/cm²
Thermal	Human Industrial	~0.1% ~3%	60 μW/cm² ~1-10 mW/cm²
Vibration	~Hz–human ~kHz–machines	25~50%	~4 μW/cm³ ~800 μW/cm³
RF	GSM 900 MHz WiFi	~50%	0.1 μW/cm² 0.001 μW/cm²

Harvesting Thermal Energy

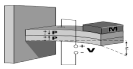
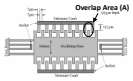
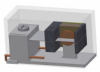


Thermocouple



Thermopiles
- thermally in parallel
- electrically in serial

Harvesting Vibration Energy

Piezoelectric	Electrostatic	Electromagnetic
		
Vibration → beam bending (strain) Piezoelectric material converts mechanical strain into electrical energy	Vibration → motion of oscillating mass Comb overlap area (A) change Comb capacitance (C) change Voltage change at constant charge (Q)	Vibration → motion of magnetic field Current flows in the static copper coil
	$C = \frac{\varepsilon_0 A}{d}$ $Q = cv$	

Storing Energy

- Scavenged energy is not constant
- Power not available on-demand
- High peak power not available
- An ideal energy storage device:
  - Infinite shelf life
  - Negligible leakage
  - Unlimited capacity
  - Negligible volume
  - No need for energy conversion
  - Efficient energy acceptance and delivery

…Ideal battery doesn't exist

Storage Options



	Li-Ion	Thin Film Rechargeable	Super Cap
Recharge Cycles	100s	5k-10k	Millions
Self Discharge	Moderate	Negligible	High
Charge Time	Hours	Minutes	Sec-Minutes
Physical Size	Large	Small	Medium
Capacity	0.3-2500mAHr	12-700uAHr	10-100uAHr
Environmental Impact	High	Minimal	Minimal

Thin-Film Battery

- Small, electrochemical batteries fabricated to deposit thin layers of battery materials
- Main Features:
  - Superior Cycle Life
  - High Energy Density
  - Flexible packaging options
  - Negligible leakage
  - Rapid recharge
  - Broad temperature performance

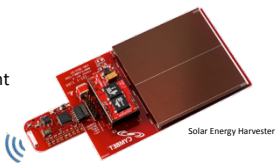
Thin-Film Battery

- **Cymbet**
  - Surface-mount
  - Packaged in QFN package
  - No harmful gases, liquids or special handling procedures
  - EnerChip CBC050 example
    - Output Voltage: 3.8V
    - Capacity: 50 µAh
    - Package: 16-pin M8 QFN
    - Size: 8 x 8 x 0.9 mm

- **Infinite Power Solutions**
  - Flexible, electrolyte based rechargeable lithium battery
  - Very thin: 0.11mm
  - Flexible
  - >10,000 recharge cycles
  - MEC101-7P example:
    - Output Voltage: 4.2V
    - Capacity: 700 µAh
    - Size: 25.4 x 25.4 x 0.11mm

Solar Energy Harvester

- Solar Energy Harvesting module for eZ430-RF2500
- Works in low ambient light
- Negligible self-discharge
- 400+ transmission with no light
- Adaptable to any sensor and RF network



eZ430-RF2500T
Wireless Target