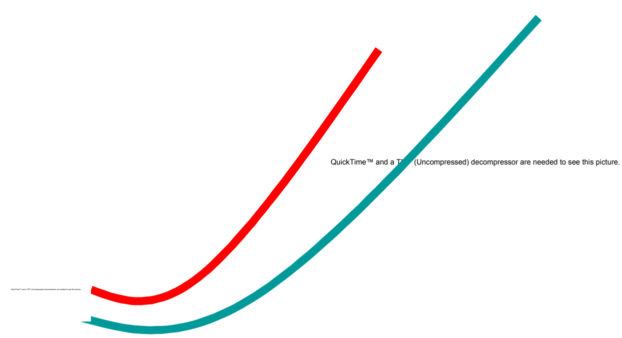
# Energy of Wireless Devices

# The Showstopper: Energy

- Need long lifetime with battery operation
  - No infrastructure, high deployment & replenishment costs
- Continual improvement in functionality, size, weight, and power
  - 1.6x/year in DSP power
  - sensing and RF components based on MEMs
- But
  - energy to wirelessly transport bits is ~constant
    - Shannon, Maxwell
  - fundamental limit on ADC speed*resolution/power
  - no Moore's law for battery technology
    - ~ 5%/year



Single-chip Wireless
Sensor Node

The Future

# Approaches to reduce energy consumption

- OS turns off parts of the computer when are not in use (mostly IO devices such as display)
- Application program uses less energy, possibly degrading quality of the user experience
- Which hardware/software component takes most energy?

# Hardware Issues

- Battery
  - Handheld devices: disposable batteries,
  - Laptops: rechargeable batteries
- Multiple power states for CPU, memory and I/O devices
  - Sleeping
  - Hibernating
  - Off
- Transition between power states:
  - Idle for a certain period of time, transition into lower power state
  - Activated when it is accessed

# OS Issues

- Keep track of the states of different devices
- Which device to transition into low-power state?
- Window's ACPI - Advanced Configuration and Power Interface
- OS sends commands asking the device driver to report on device's states (power information)

# Display Energy Management

- The biggest energy consumption
- Reason
  - Require backlit to get a bright sharp image
- What solutions would reduce display energy?
  - shut down the display if there is no activity for some number of minutes.
  - divide the screen into zones and turn on only zones where the active window resides (work by Flinn and Satyanarayanan)
  - Change color mapping scheme

# Hard Disk

- Disk takes substantial energy
  - spinning at high speed, even if there are no accesses.
- What would be the solution to decrease energy?
  - spin the disk down after a certain idle time of activities.
  - When it is needed, it is spun up again
  - Disk cache in RAM can save energy
    - If a needed block is in the cache, the idle disk does not have to be restarted
  - Another possibility is to keep application programs informed when disk is down.

# Memory

- Two options to save energy with memory:
  - cache is flushed and then switched off (hibernation)
  - write content of memory to disk and switch off the memory
- When memory is shut off
  - CPU has to shut off or has to execute out of ROM;
  - If CPU is off and interrupt wakes it up, it has to read from ROM to load the memory.
- What are the tradeoff?
- Multiple power-mode
  - Active
  - Nap
  - Standby
  - Power-down

# CPU - Energy-Efficient Mobile Multimedia Devices (Research, SOSP 2003)

Mobile devices

- Running multimedia apps (e.g., MP3 players, DVD players)

- Running on general purpose systems

– Demanding quality requirements

- System resources: high performance
- OS: predictable resource management

– Limited battery energy


- System resources: low power consumption
- OS: energy as first-class resource

# Wireless Communications is a Major Energy Hog

- Energy/bit ÷ Energy/op large even for short ranges!

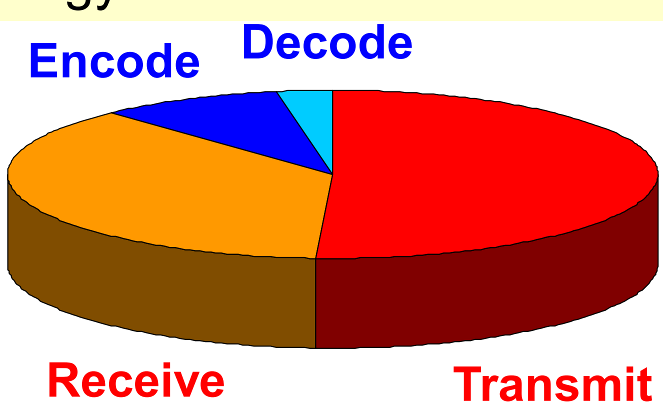
**Mote-class Node**

| | | | |
|---|---|---|---|
| Transmit | **720 nJ/bit** | Processor | **4 nJ/op** |
| Receive | **110 nJ/bit** | **~ 200 ops/bit** | |

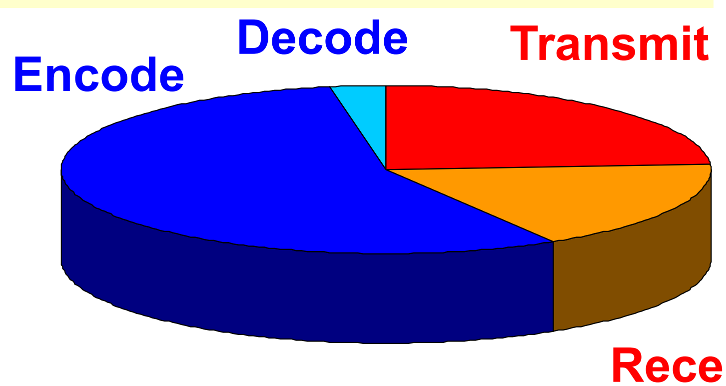
**WINS-class Node**

| | | | |
|---|---|---|---|
| Transmit | **6600 nJ/bit** | Processor | **1.6 nJ/op** |
| Receive | **3300 nJ/bit** | **~ 6000 ops/bit** | |

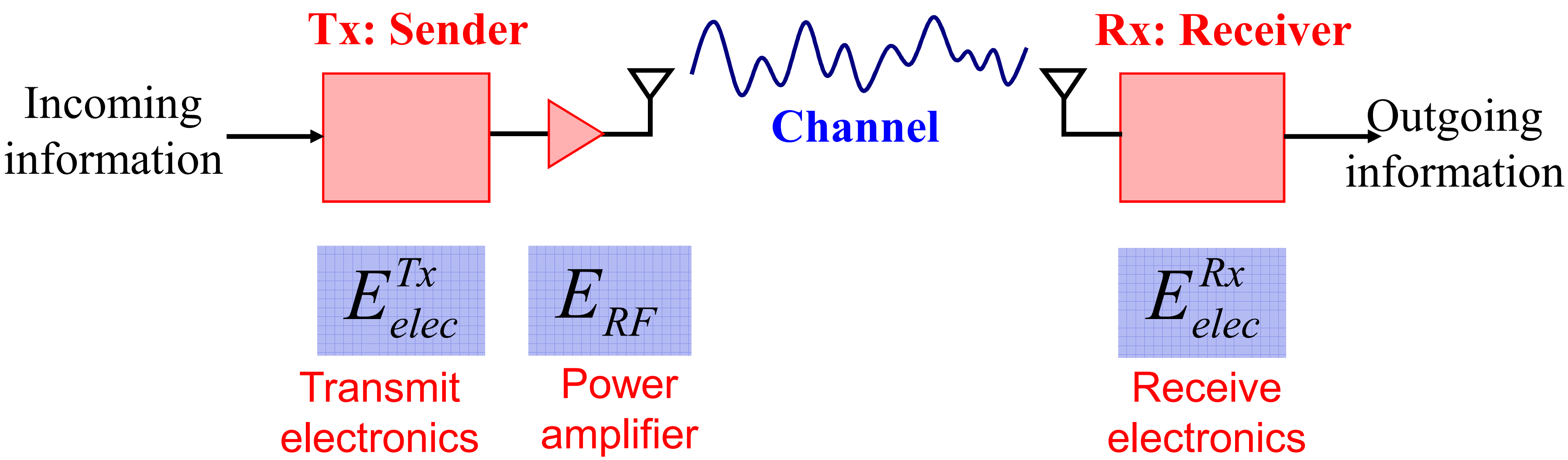
Energy breakdown for acoustic

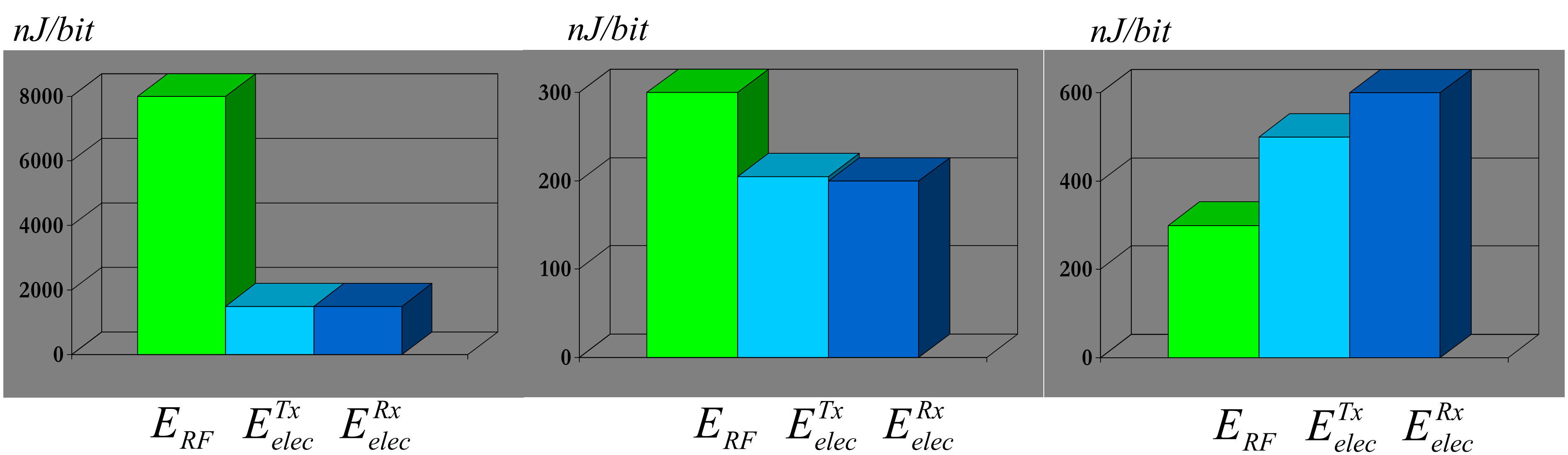



Energy breakdown for image



# Radio Power Consumption



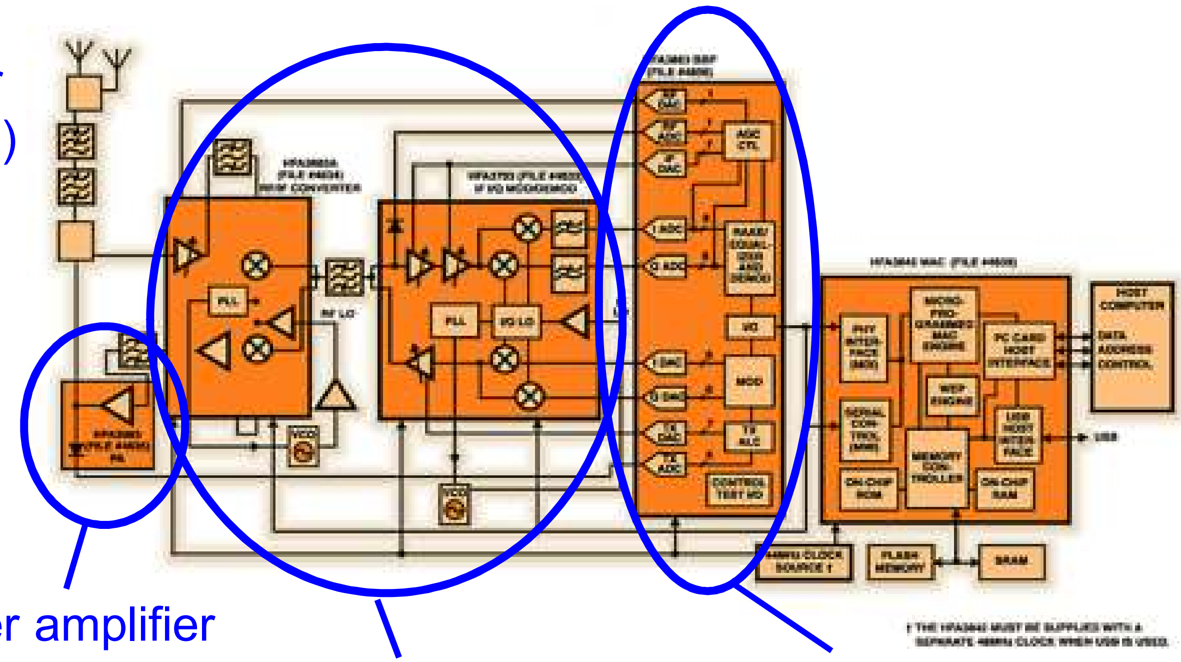




**~ 1 km (GSM)** **~ 50 m (WLAN)** **~ 10 m (Mote)**

# Radio Electronics Trends

Radiated power
63 mW (18 dBm)

Intersil PRISM II
(Nokia C021 wireless LAN)



Power amplifier
600 mW
(~11% efficiency)

Analog electronics
240 mW

Digital electronics
170 mW

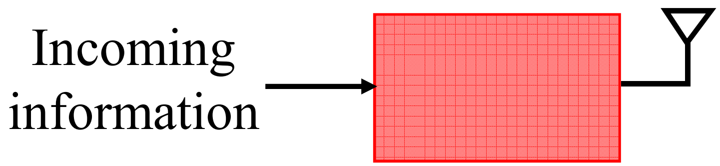
- Trends:
  - Move functionality from the analog to the digital electronics
  - Digital electronics benefit most from technology improvements
  - Analog a bottleneck
  - Digital complexity still increasing (robustness)

# What can be done?

- Reduce energy/bit
- Increase energy availability

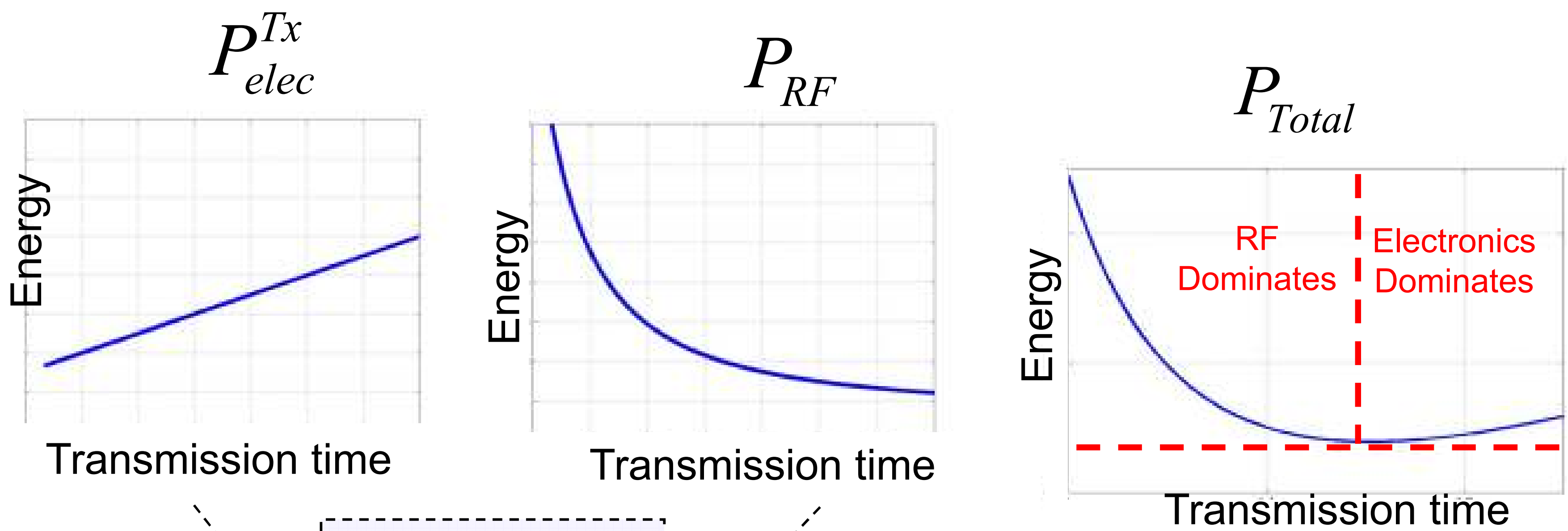
# 1. Radio Energy Management

**Tx: Sender**




- Parameter of interest:
  - energy consumption per bit

$$E_{bit} = \frac{P}{T_{bit}}$$

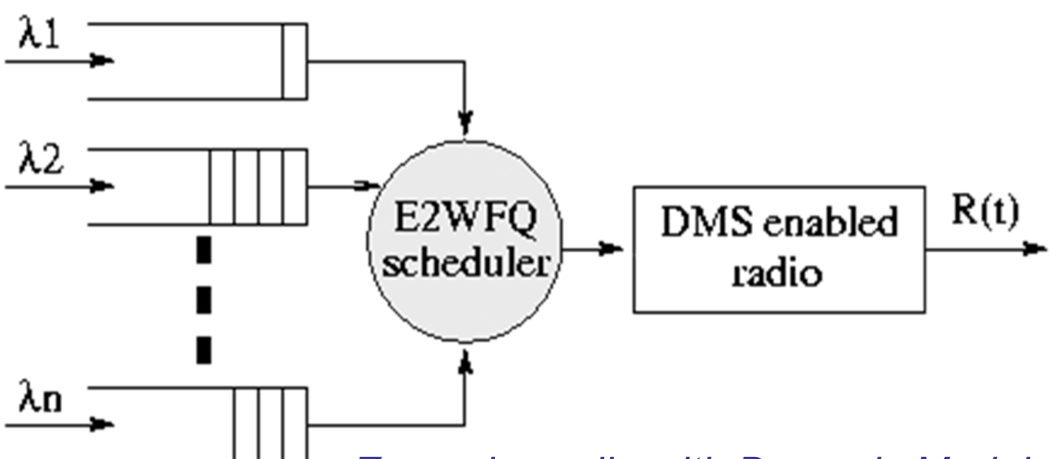



Modulation scaling
fewer bits per symbol

Code scaling
more heavily coded

# MAC: Scaling for Energy

- Radios with scalable modulation and coding
- MAC protocol that decides
  - Which node transmits
  - What packet
  - At what time
  - On what channel
  - With what RF power
  - **What modulation and coding setting**

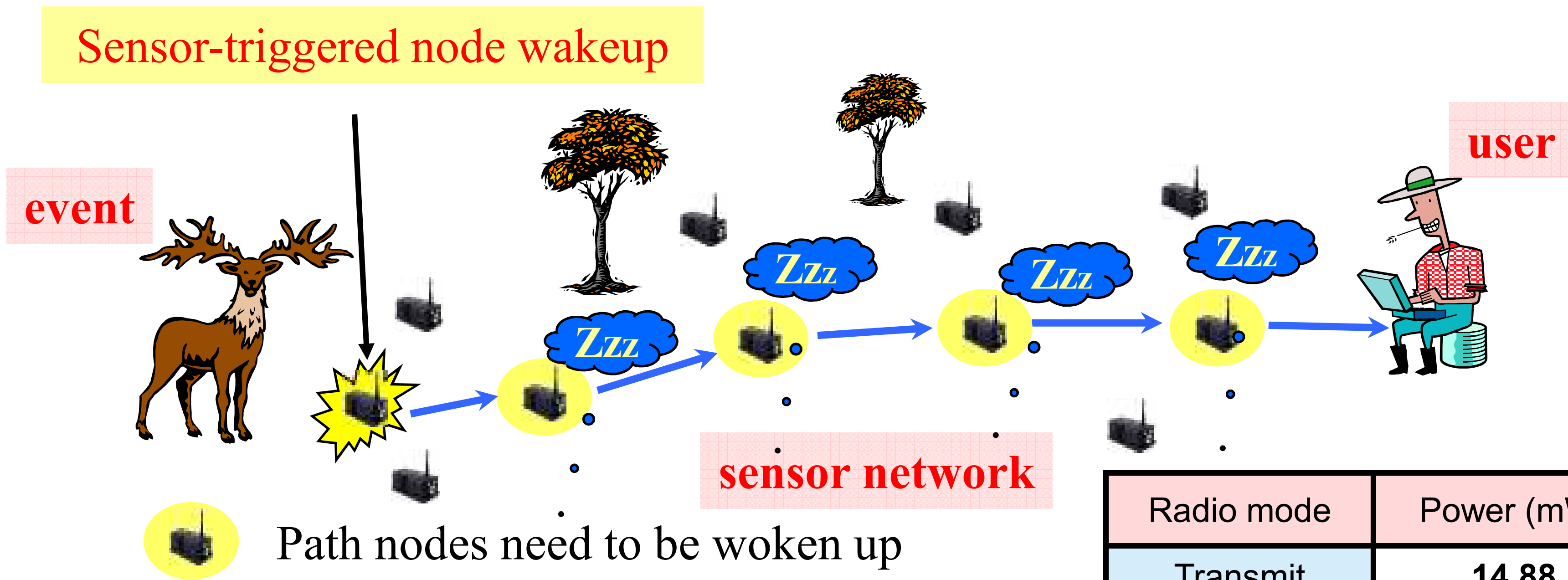



*Example: radio with Dynamic Modulation Scaling & scaling-aware scheduler*

# Shutdown

- Radio modes: active, idle, shutdown, transient
- Transient period
  - Active/idle to sleep is short and can be ignored
  - Sleep to active/idle period, $T_{ON}$, is not
    - PLL in the frequency synthesizer takes time to settle
    - $P_{tr} = 2*P_{syn}$
    - $T_{ON}$ is O(10)-O(100) uS
    - mixer & power amp startup can be ignored
- Problem: $T_{ON}$ is significant fraction of packet duration
  - Packet sizes small in sensor nets (reporting events)
- Leads to high energy per bit!
- Radios with fast start-up and acquisition

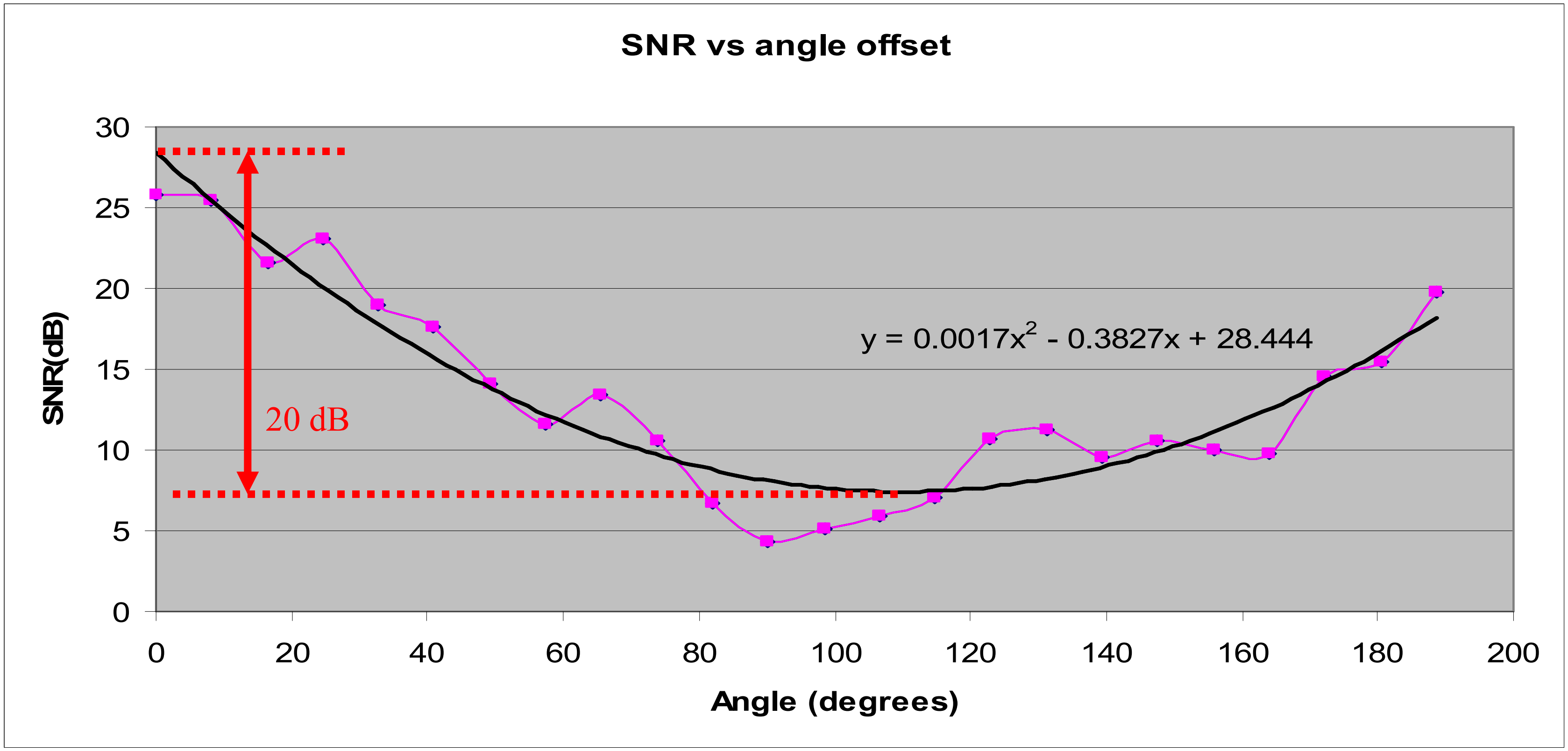
# On-demand Data-driven Wakeup




| Radio mode | Power (mW) |
|---|---|
| Transmit | **14.88** |
| Receive | **12.50** |
| Idle | **12.36** |
| Sleep | **0.016** |

- How to wakeup?
- Duty cycle the radio
  - trade-off between energy and latency
- Wake-up circuit & protocols exploiting them
  - instantly wake up remote receiver radio when needed
  - minimize spurious wake ups & interference, and their impact
    - match destination address in addition to preamble
    - cheap directional antennas

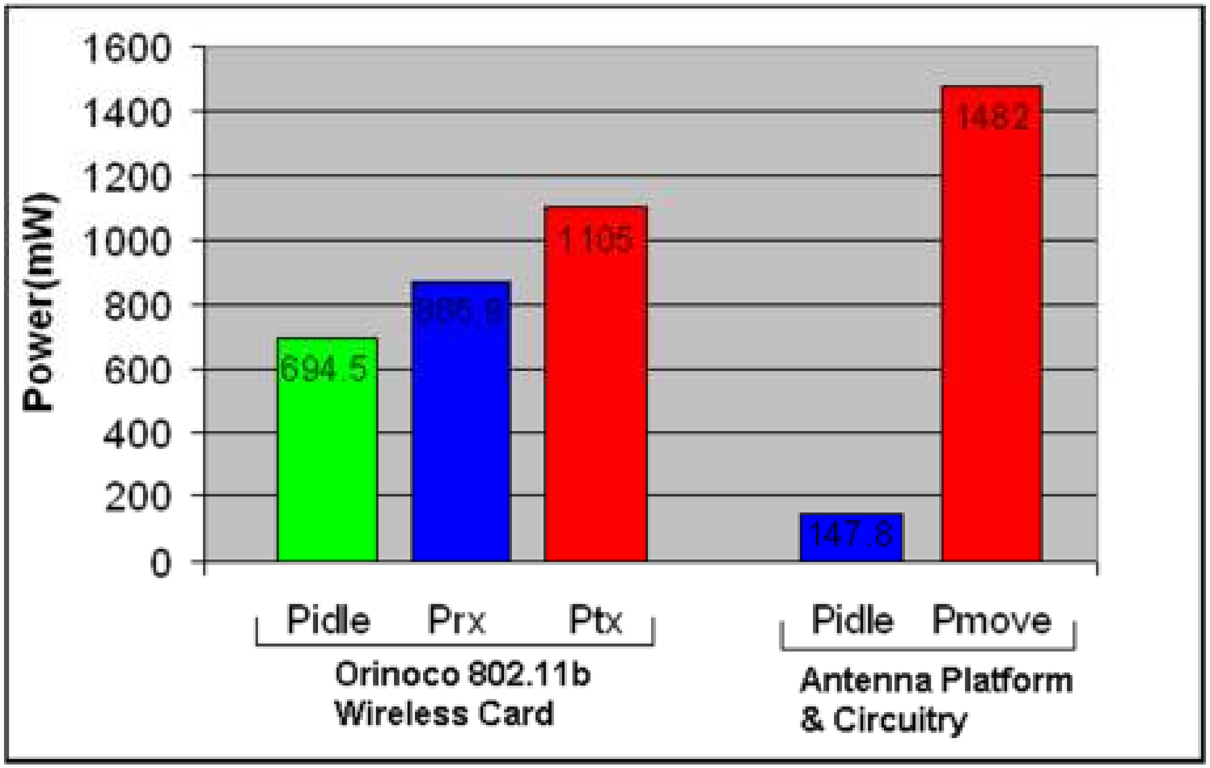
# 2. Reduced Path Loss via Directional Antenna




Microceptor QD2402
[Pon & Wu, UCLA, 2003]

- Smart antenna
  - Signal processing (beamforming)
  - Low transient cost, high quiescent cost
- Reconfigurable antennas
  - Mechanical articulation, electrical reconfiguration
  - High transient cost, low quiescent cost

# Energy: Communication vs. Articulation




Articulated Microceptor QD2402
[Pon & Wu, UCLA, 2003]

- 51 degrees/second latency
- Breakeven point: # of bits vs. gain in SNR
- Spend upfront energy and save on subsequent per-packet energy

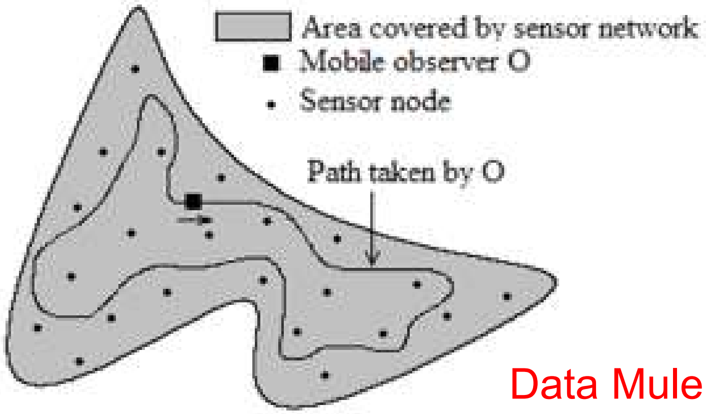
# 3. Exploiting Articulation & Mobility for Energy

- Rich source of system lifetime improvement
  - Nodes with articulated appendages
  - Nodes that move
    - Controlled, predictable, unpredictable
    - Restricted, unrestricted
- Opportunities
  - Better communication & sensing channel
  - Diversity gain due mobility
  - Mechanical transport of bits & energy
  - Better energy harvesting
- Challenges
  - Platforms with articulation & mobility
  - Protocols and collaboration algorithms to exploit mobility
  - Understanding the fundamental impact of mobility on lifetime

AmigoNode

RoboMote

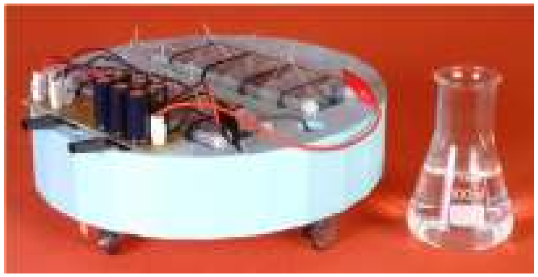
NIMS




Data Mule

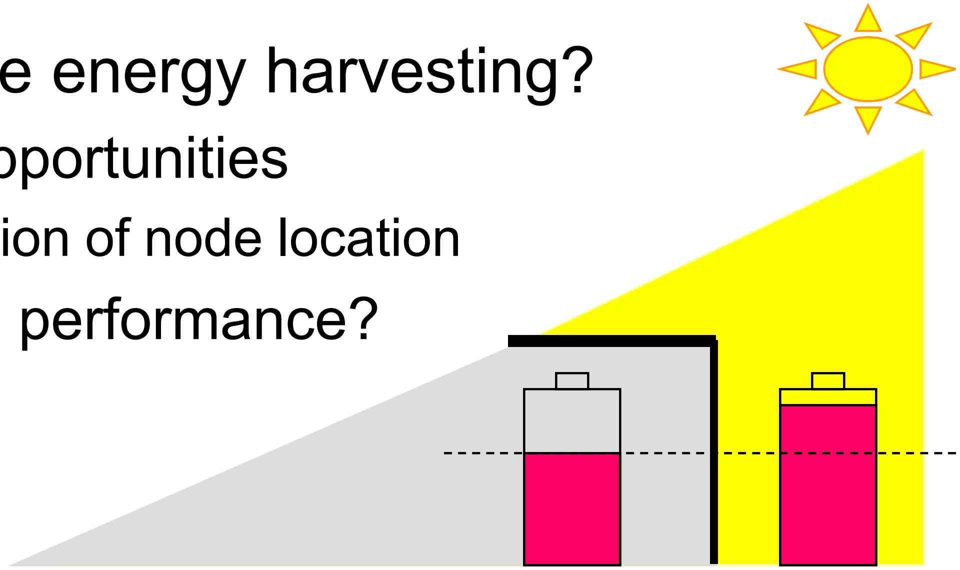
# 4. Beyond Reduction: Energy Harvesting

- Sensor nodes that extract energy from the environment and store in a capacitor or battery
  - Wind
  - Solar
  - Vibration/Motion
  - Chemical



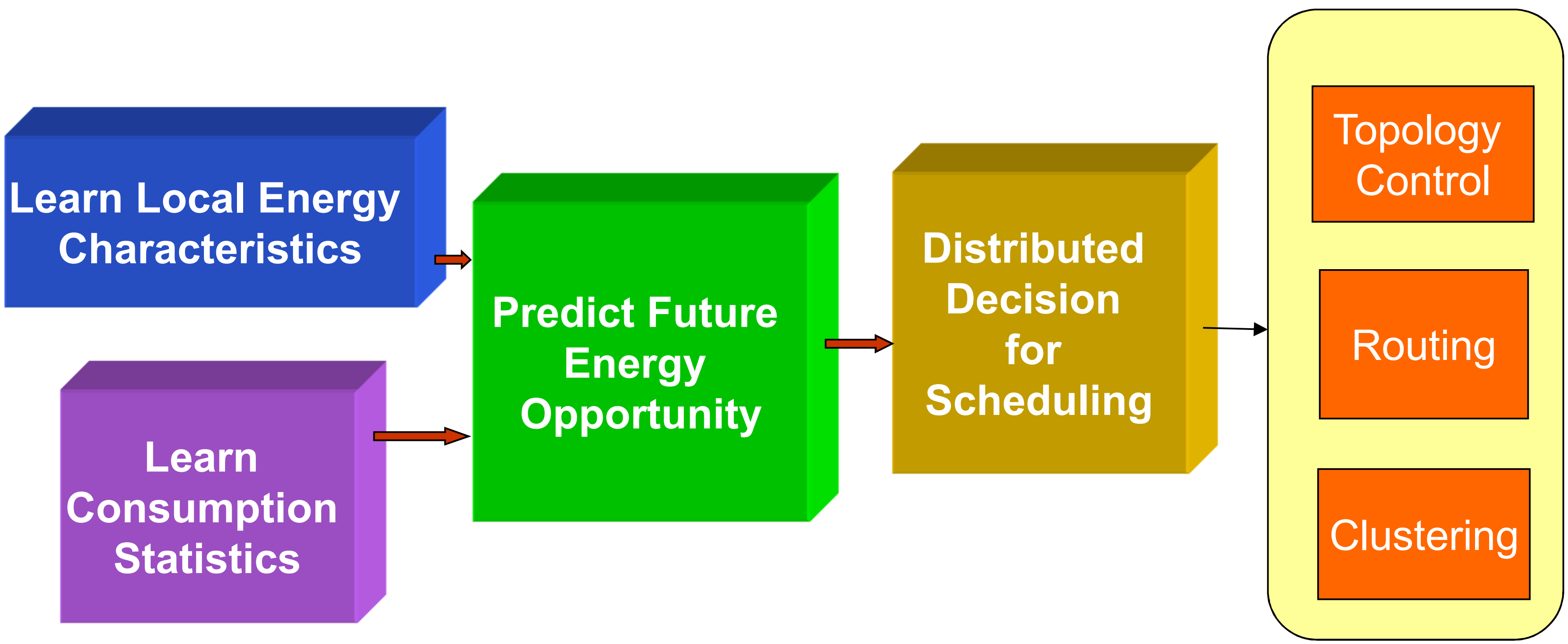
Prototypes from IASL, UWE, Bristol.

- Challenge: how to manage energy harvesting?
  - Variation in harvesting opportunities
    - E.g. light level is a function of node location
  - How to extract maximum performance?

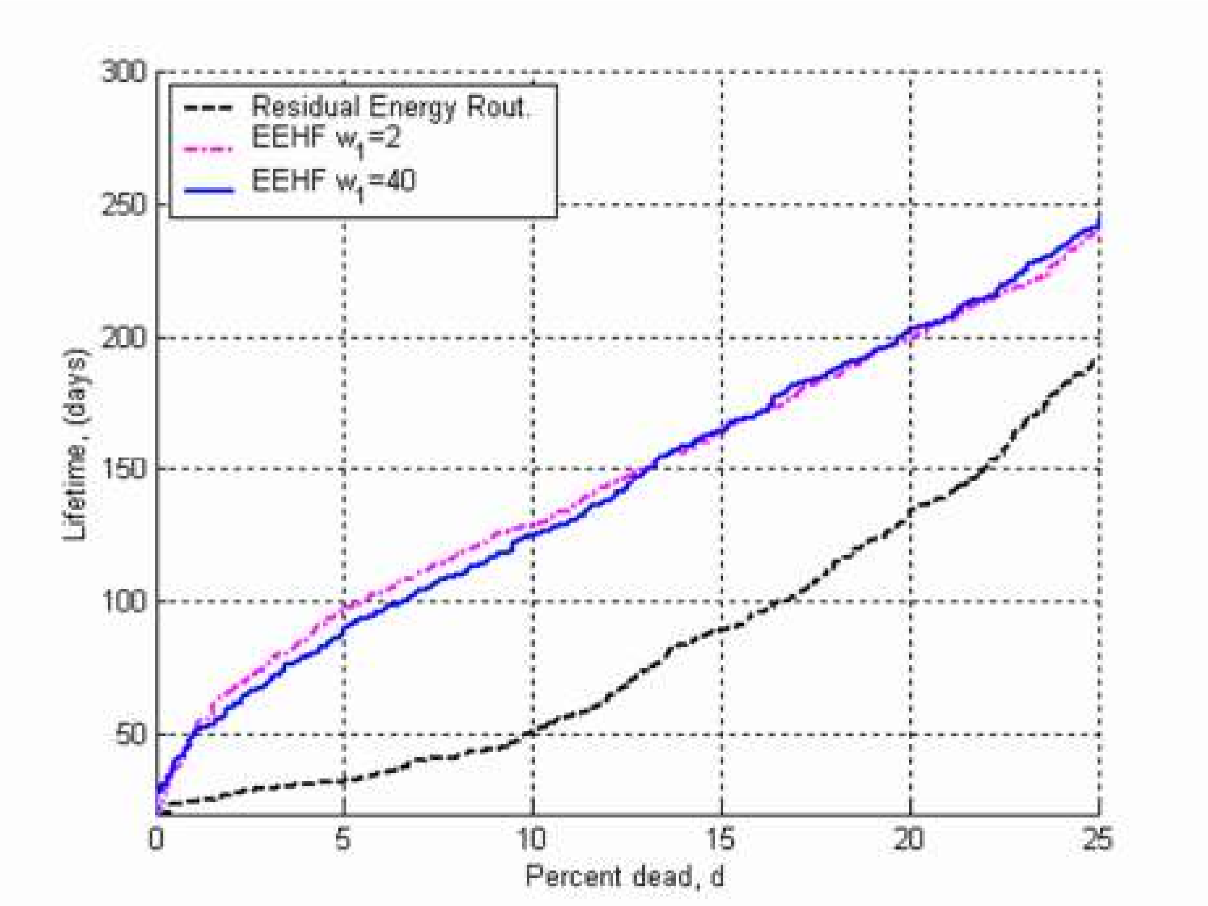


# Harvesting-aware Network-level Tasking

- Tasking aware of battery status & harvesting opportunities
  - Richer nodes take more load
  - Looking at the battery status is not enough
- Learn the energy environment



# Example: Solar Harvesting Aware Routing




morning

Afternoon

Simulation using light traces from James Reserve

HelioMote Platform

# Summary

- Energy-efficient radios
  - Energy-performance scalability for long range
  - Efficient shutdown and wake-up for short range

- Directional antennas
  - Electrical or mechanical reconfiguration of directional elements

- Platforms and algorithms to exploit mobility and articulation
  - Better communication & sensing channel
  - Diversity gain due mobility
  - Mechanical transport of bits and energy
  - Better energy harvesting

- Energy harvesting
  - Network operation that is aware of spatio-temporal characteristics of environmental energy availability

# Challenges

- Technologies
  - Energy-efficient and energy-scalable components
    - Radios, reconfigurable antenna, sensor processing (image, biochem)
  - Energy harvesting
    - Wind, solar, motion, vibration, chemical
  - Ad hoc infrastructure elements / hierarchy
    - Energy & data mule, Mobile Microservers
    - EM and wired energy delivery
- Techniques
  - Energy-latency-accuracy-coverage trade-offs
  - Algorithms: energy-efficient, battery-aware, harvesting-aware
  - Distributed in-network processing
- Metrics, Benchmarks, Tools, and Testbeds
  - Energy-metrics for sensing, signal processing, event detection, and communication protocols
  - Benchmark suite of representative functions
  - Simulators with models of energy producers and consumers
  - Instrumented testbeds