Leveraging Multiple Heterogeneous Radios for Energy-efficient Routing

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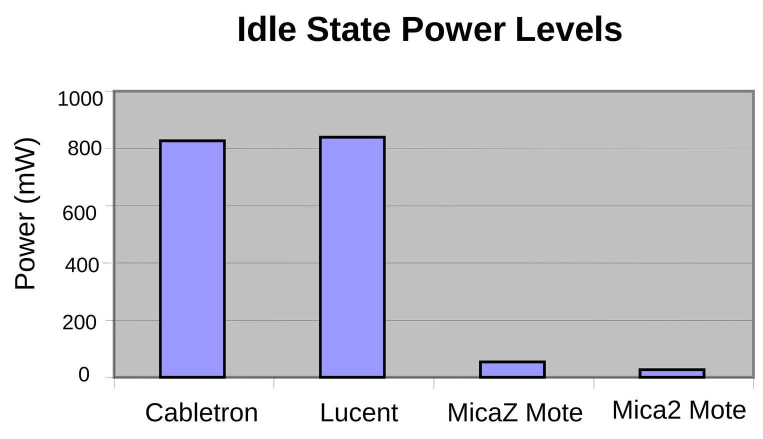
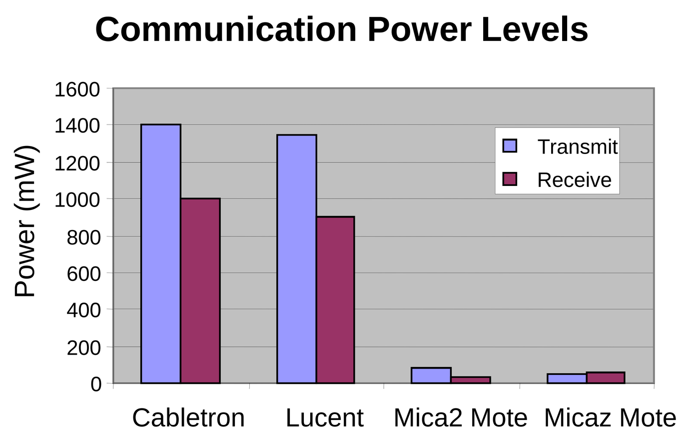
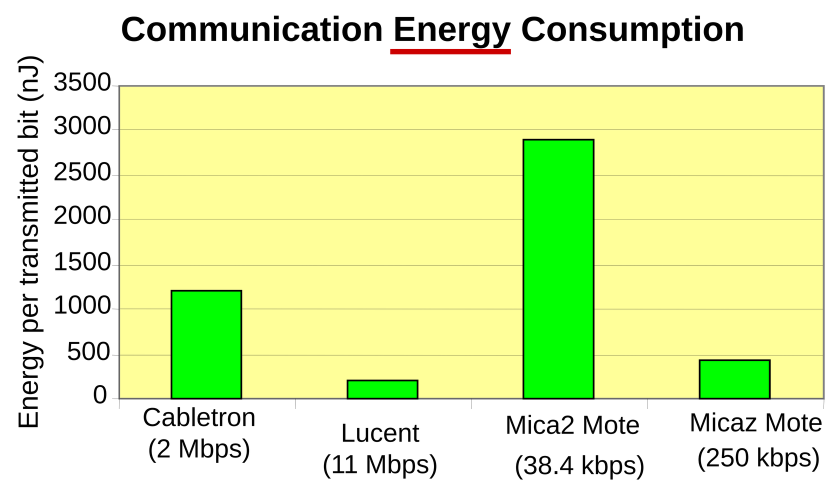
Energy-Efficient Selection of Radio(s) for Sensor Networks

- Goals
  - Increase sensor network lifetime
  - Reduce overall energy consumption
- Challenges
  - Evaluate energy/performance trade-offs for available radios
  - Manage selection of appropriate radio(s) in an energy-efficient manner
  - Maintain effective network performance (e.g., low delay)
- Radio Energy Consumption
  - Idling costs
    - Energy consumed per unit time in the idle state
  - Communication costs
    - Energy consumed per transmitted bit







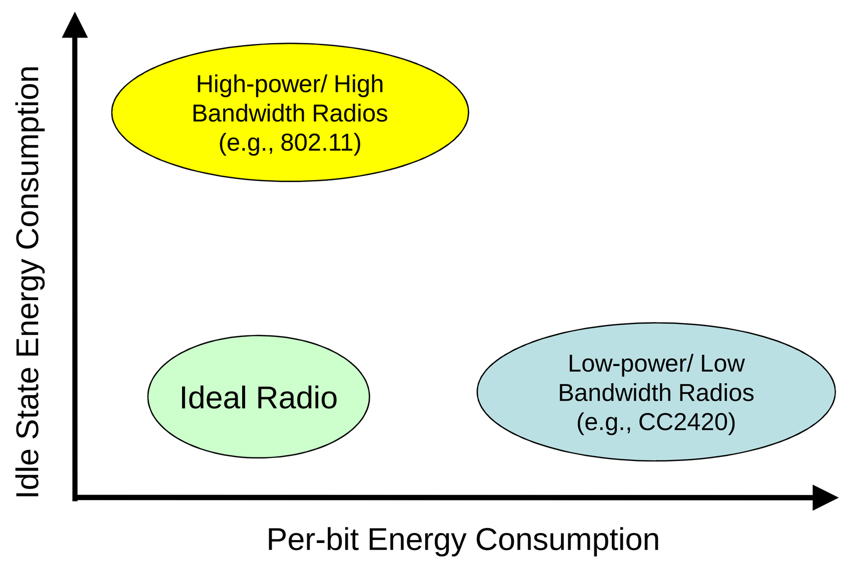
- Comparison of Power Levels for Different Radios
  - Low-power/low-rate radios apparently fare better on both counts
    - Low *idling* cost
    - Low *power* level in the communication states

Do lower **power** levels always mean less **energy** consumption in total ?

- Energy Per Transmitted Bit
  - High-power radios
    - Higher data rate
    - Shorter transmission time
    - Lower energy consumption for every bit transmitted

The Quest for the Ideal Radio

- Current Radio Selection
  - Approach
    - Choose a single radio that best suits the characteristics of sensor network
  - Trade-off
    - Sacrifice either low idling cost or low energy per bit

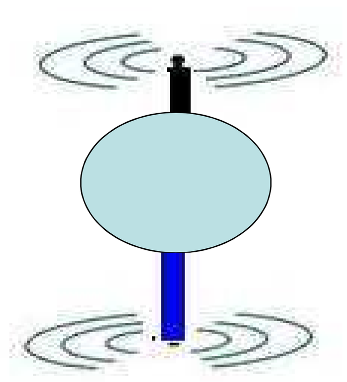


  - Determining Factor
    - Sensor nodes spend most of their time in the idle state
  - Solution
    - Select radios that minimize idle state energy consumption (i.e., low-power/ low-bandwidth radios like CC1000)

But why should we be constrained by the limit of one radio?

Dual Radio Approach

- Main Idea – Get the best of both worlds!
  - Add a high-power radio to leverage its low per-bit transmission cost
  - Retain the existing low-power radio to utilize its low idling cost
- Challenges of using a High-power Radio
  - High idle state overhead
  - Non-negligible state transition costs
- Our Solution
  - Reduce idling energy consumption by switching off the high-power radio when not in use
  - Reduce per-bit transmission costs by transmitting data using the high-power/high-rate radio
  - Amortize transitions costs from OFF to ON by buffering data and sending in a large burst



How many bytes do we need to buffer to achieve a net energy savings?

When does it pay off to transmit with the high-power radio?

- Break-even Point
  - The minimum data size a high-power/high-rate radio needs to buffer so that energy can be saved in comparison to a low-power/low-rate radio
  - How to calculate the break-even point?
    - Find the cost of sending *s* bytes by the sensor radio $E_{sr}(s)$
    - Find the cost of sending s bytes by the 802.11 radio $E_{802.11}(s)$
    - The value of *s*, for which $E_{802.11}(s) = E_{sr}(s)$ is the **break-even point**

$$E_{SR}(s) = (P_{tx}^{SR} + P_{rx}^{SR})\frac{s}{R_{SR}}$$

Transmit/Receive Power of the Sensor Radio

Data Rate of the Sensor Radio

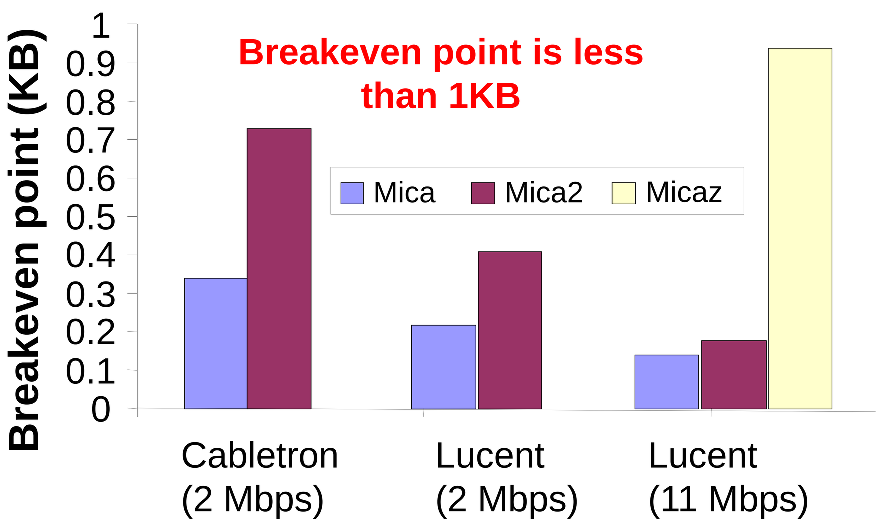
$$E_{802.11}(s) = E_{wakeup} + E_{SR}(wakeup) + E_{idle} + (P_{tx}^{802.11} + P_{rx}^{802.11})\frac{s}{R_{802.11}}$$

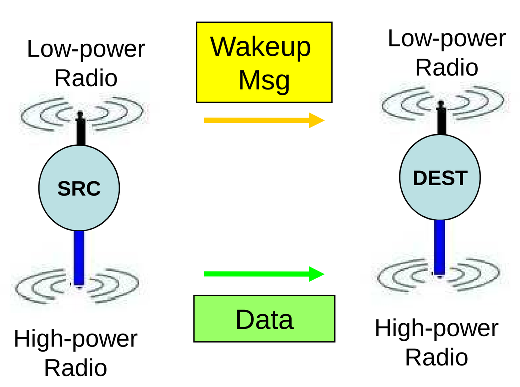
The energy spent in waking up the sender and receiver 802.11 radios

The energy cost of sending wake-up messages through the sensor radio

The energy consumed by the two 802.11 radios in idle state

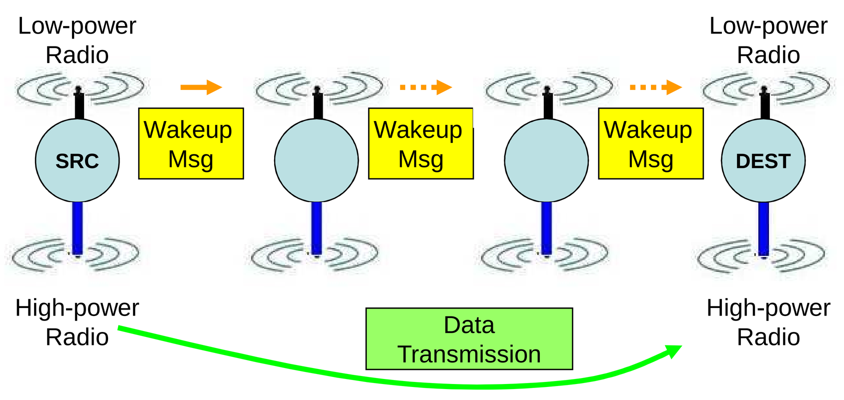
Single-hop case





Destination is reachable in a single hop by both radios

- Can we go more than one-hop?
  - High-power radios have higher transmission range
  - Nodes that are multi-hops away through the sensor radio may be **directly reachable** through the 802.11 radio



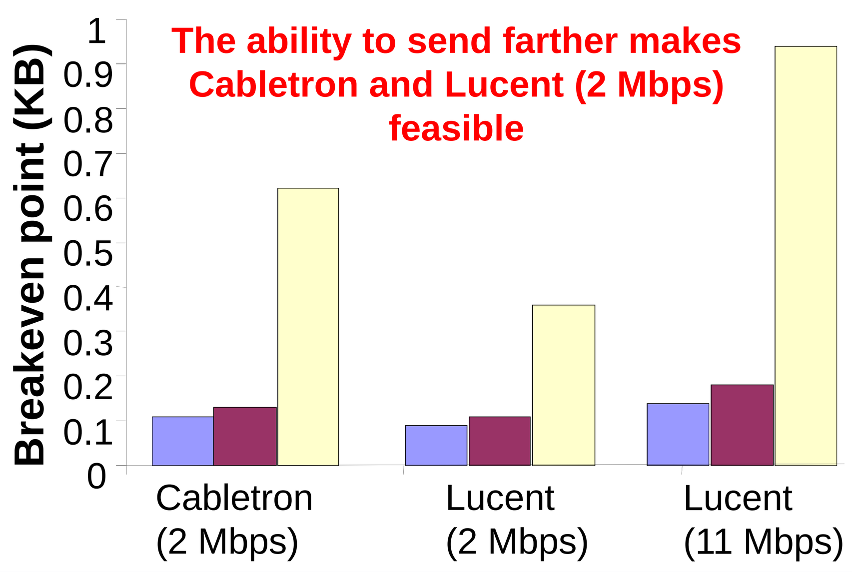
Hop-distance in terms of sensor radio

$$E_{SR}^{multihop} = nE_{SR}(s)$$

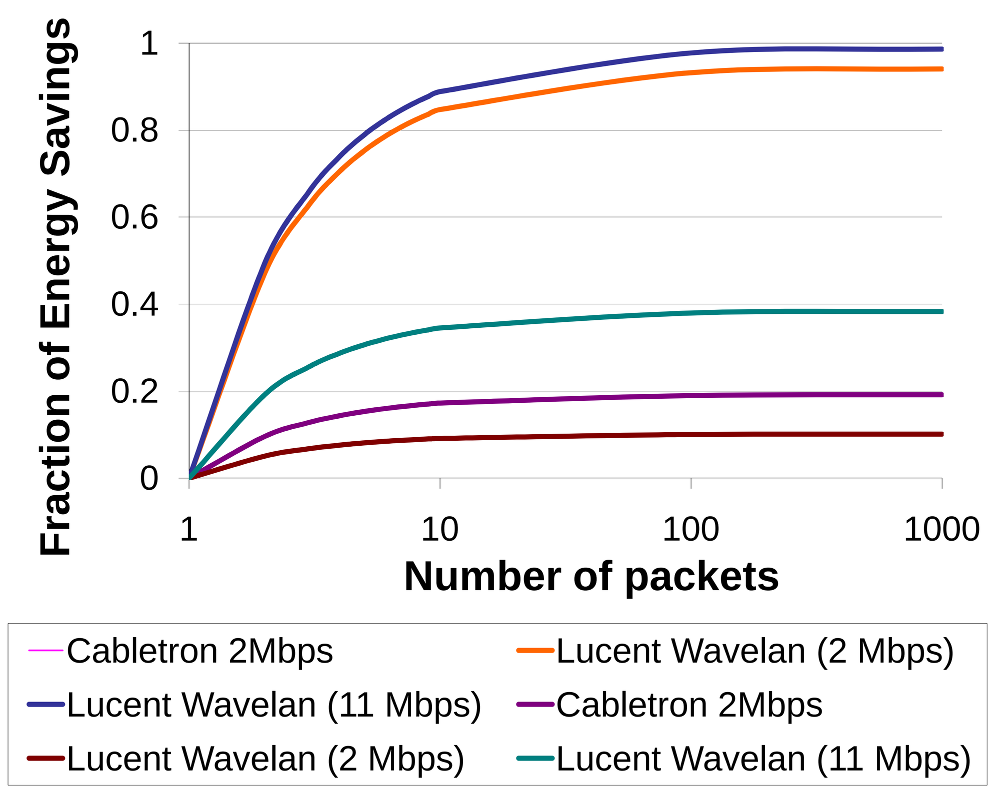
$$E_{802.11}^{multihop} = E_{802.11}(s) + (n-1)E_{SR}(wakeup)$$

Find *s* for which, $E_{802.11}^{multihop}(s) = E_{SR}^{multihop}(s)$

Multi-hop case



What if we go over the break-even point?



- Trade-offs of larger bursts
  - Lower energy
  - Higher delay
- "Good" operating point
  - Save energy with 1 – 10 KB
  - Diminishing energy gains

Future Directions

- Implement and evaluate our proposed dual radio scheme in a sensor test bed
- Investigate the impact of "real-world" issues on break-even point
  - Channel Contention
  - Congestion