CS649
Sensor Networks
Lectures 13-14: Medium Access Control

Andreas Terzis
http://hinrg.cs.jhu.edu/wsn06/

Outline

- Background in MAC protocols
  - Role and features of MAC protocols
  - Scheduled access vs. Randomized access
  - Additional WSN requirements
- Two Examples
  - S-MAC
  - BMAC

Characteristics of Sensor Network

- A special wireless ad hoc network → Scalability & Self-configuration
  - Large number of nodes
  - Battery powered → Energy efficiency
  - Topology and density change → Adaptivity
  - Nodes for a common task → Fairness not important
  - In-network data processing → Message-level Latency
- Sensor-net applications
  - Sensor-triggered bursty traffic
  - Can often tolerate some delay → Adaptivity
    - Speed of a moving object places a bound on network reaction time → Trade for energy

MAC and Its Classification

- Medium Access Control (MAC)
  - When and how nodes access the shared channel
- Classification of MAC protocols
  - Scheduled protocols
    - Schedule nodes onto different sub-channels
    - Examples: TDMA, FDMA, CDMA
  - Contention-based protocols
    - Nodes compete in probabilistic coordination
    - Examples: ALOHA (pure & slotted), CSMA

MAC Attributes

- Collision avoidance
  - Basic task of a MAC protocol
- Energy efficiency
- Scalability and adaptivity
  - Network size, node density and topology change
- Channel utilization
- Latency
- Throughput
- Fairness

Primary

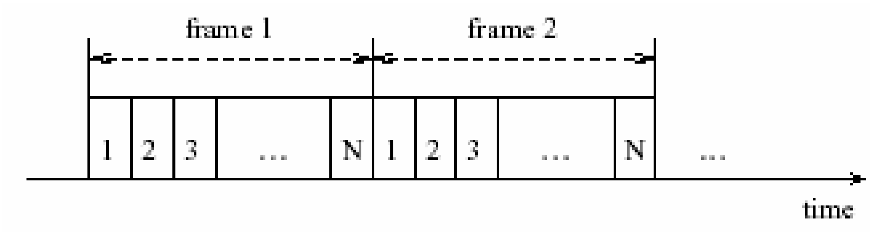
Secondary

Energy Efficiency in MAC Design

- Energy is primary concern in sensor networks
- What causes energy waste?
  - Collisions
  - Control packet overhead
  - Overhearing unnecessary traffic
  - Long idle time
    - Bursty traffic in sensor-net apps
    - Idle listening consumes 50—100% of the power for receiving ⟵ Dominant factor

Scheduled Protocols

- TDMA



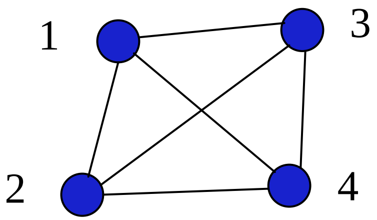
  - Advantages
    - No collisions
    - Energy efficient — easily support low duty cycles
  - Disadvantages
    - Bad scalability and adaptivity
      - Difficult to accommodate node changes
      - Difficult to handle inter-cluster communication
    - Requires strict time synchronization

Scheduled Protocols

- Polling
  - A master plus one or more slaves (star topology)
  - The master node decides which slave can send by polling the corresponding slave
  - Only direct communication between the master and a slave
  - A special TDMA without pre-assigned slots
  - Examples
    - IEEE 802.11 infrastructure mode (CFP)
    - Bluetooth *piconets*

Scheduled Protocols

- Self-Organization — by Sohrabi and Pottie
  - Have a pool of independent channels
    - Frequency band or spreading code
    - Potential interfering links select different channels
  - Talk to neighbors in different time slots
  - Sleep in unscheduled time slots
  - Looks like TDMA, but actually FDMA or CDMA
    - Any pair of two nodes can talk at the same time
  - Low bandwidth utilization



Scheduled Protocols

- Bluetooth
  - Target for wireless personal area network (WPAN)
    - Short range, moderate bandwidth, low latency
    - IEEE 802.15.1 (MAC + PHY) is based on Bluetooth
  - Nodes are clustered into piconets
    - Each piconet has a master and up to 7 slaves – scalability problem
    - The master polls each slave for transmission
  - Frequency-hopping CDMA between clusters
  - Multiple connected piconets form a scatternet
    - Different to handle inter-cluster communications

Scheduled Protocols

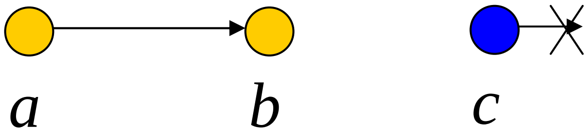
- Bluetooth (Cont.)
  - How about Bluetooth radio with sensor networks?
  - Scalability is a big problem
  - Lack of multi-hop support
    - No commercial Bluetooth radio supports *scatternet* so far
    - Use two radios – expensive and energy inefficient
    - A node temporarily leave one piconet and joins another – high overhead and long delay

Scheduled Protocols

- LEACH: Low-Energy Adaptive Clustering Hierarchy — by Heinzelman, et al.
  - Similar to Bluetooth
  - CDMA between clusters
  - TDMA within each cluster
    - Static TDMA frame
    - Cluster head rotation
    - Node only talks to cluster head
    - Only cluster head talks to base station (long dist.)
  - The same scalability problem

Contention-Based Protocols

- Contention-based protocols
  - CSMA — Carrier Sense Multiple Access
    - Listening before transmitting
    - Not enough for multi-hop networks (collision at receiver)



Hidden terminal: *a* is hidden from *c*'s carrier sense

  - CSMA/CA (CA stands for Collision Avoidance)
    - RTS/CTS handshake before send data
    - Other nodes (e.g. node *c*) backoff

Contention-Based Protocols

- Contention-based protocols (contd.)
  - MACA — Multiple Access w/ Collision Avoidance
    - Add duration field in RTS/CTS informing other node about their backoff time
  - MACAW — improved over MACA
    - RTS/CTS/DATA/ACK
    - Fast error recovery at link layer
  - IEEE 802.11 Distributed Coordination Function (DCF)
    - Largely based on MACAW

Contention-Based Protocols

- IEEE 802.11 DCF: ad hoc mode
  - Virtual and physical carrier sense (CS)
    - Network allocation vector (NAV), duration field
  - Binary exponential backoff
  - RTS/CTS/DATA/ACK for unicast packets
  - Broadcast packets are directly sent after CS
  - Fragmentation support
    - RTS/CTS reserve time for first (fragment + ACK)
    - First (fragment + ACK) reserve time for second...
    - Give up transmission when error happens

Contention-Based Protocols

- Tx rate control — by Woo and Culler
  - Based on a special network setup
    - A base station tries to collect data equally from all sensors in the network
  - CSMA + adaptive rate control
  - Promote fair bandwidth allocation to all sensors
    - Nodes close to the base station forward more traffic, and have less chances to send their own data
  - Helps in congestion avoidance

Scheduled vs. Contention Protocols

	Scheduled Protocols	Contention Protocols
Collisions	No	Yes
Energy efficiency	Good	Bad
Scalability and adaptivity	Bad	Good
Multi-hop communication	Difficult	Easy
Time synchronization	Strict	Loose or not required

Energy Efficiency in Contention Protocols

- Contention-based protocols need to work hard in all directions for energy savings
  - Reduce idle listening – support low duty cycle
  - Reduce control overhead
  - Reduce collisions
  - Avoid unnecessary overhearing

Energy-Efficient MAC Design

- PAMAS: Power Aware Multi-Access with Signalling — by Singh and Raghavendra
  - Improve energy efficiency from MACA
  - Avoid overhearing by putting node into sleep
  - Use separate control and data channels
    - RTS, CTS, busy tone to avoid collision
    - Probe packets to find neighbors transmission time
  - Increased hardware complexity
    - Two channels need to work simultaneously, meaning two radio systems.

Energy-Efficient MAC Design

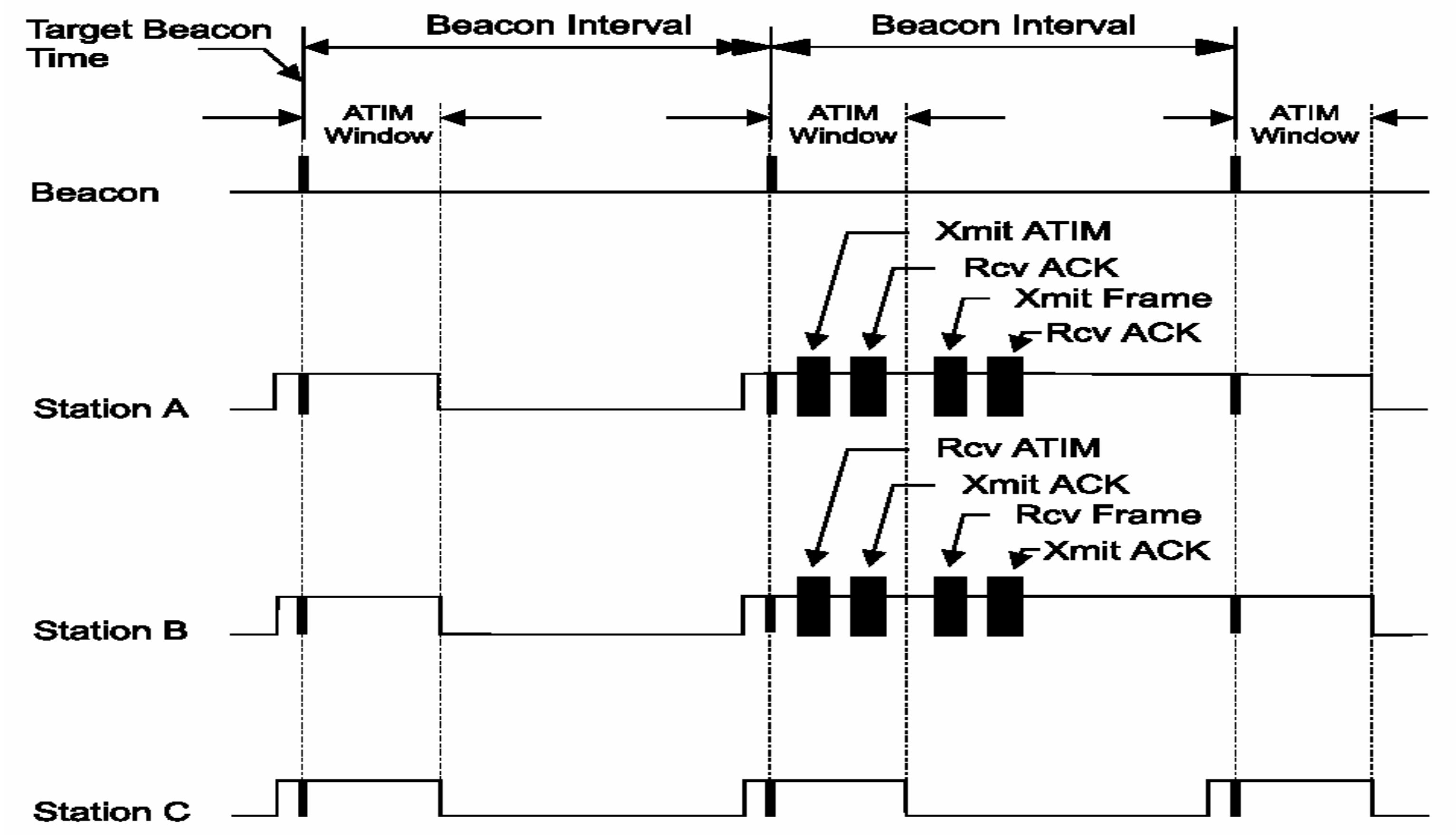
- Piconet — by Bennett, Clarke, et al.
  - Not the same piconet in Bluetooth
  - Low duty-cycle operation — energy efficient
    - Sleep for 30s, beacon, and listen for a while
    - Sending node needs to listen for receiver's beacon first, then
    - CSMA before sending data
  - May wait for long time before sending

Energy-Efficient MAC Design

- Power save (PS) mode in IEEE 802.11 DCF
  - Assumption: all nodes are synchronized and can hear each other (single hop)
  - Nodes in PS mode periodically listen for beacons & ATIMs (ad hoc traffic indication messages)
  - Beacon: timing and physical layer parameters
    - All nodes participate in periodic beacon generation
  - ATIM: tell nodes in PS mode to stay awake for Rx
    - ATIM follows a beacon sent/received
    - Unicast ATIM needs acknowledgement
    - Broadcast ATIM wakes up all nodes — no ACK

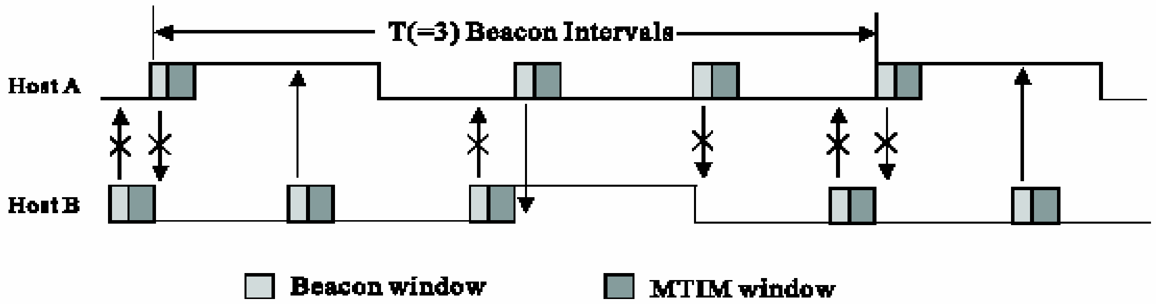
Energy-Efficient MAC Design

- Unicast example of PS mode in 802.11 DCF



Energy-Efficient MAC Design

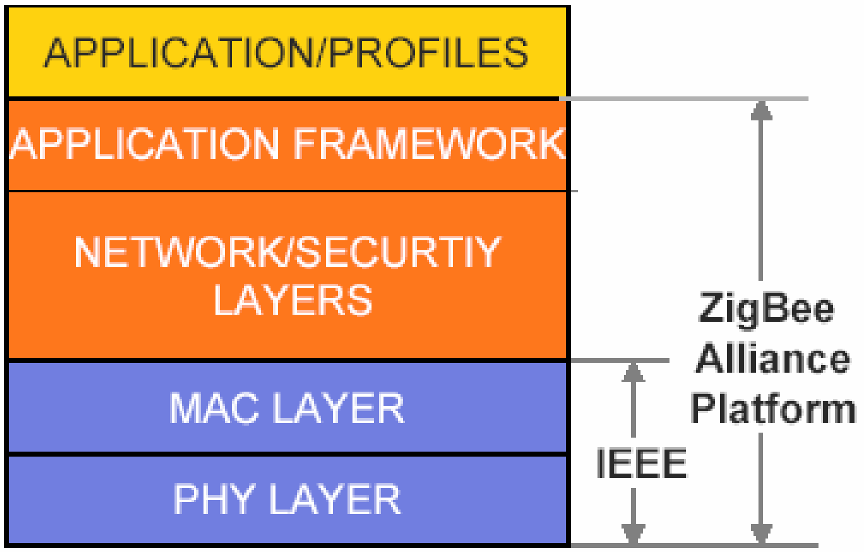
- Asynchronous sleeping – by Tseng, et al.
  - Extend 802.11 PS mode to Multi-hops
  - Nodes do not synchronize with each other
  - Designed 3 sleep patterns — ensure nodes listen intervals overlap, example:
    - Periodically fully-awake interval: similar to S-MAC



    - Problem on broadcast — wake up each neighbor

Energy-Efficient MAC Design

- ZigBee
  - Industry standard through application profiles running over IEEE 802.15.4 radios
  - Target applications are sensors networks, interactive toys, smart badges, remote controls, and home automation

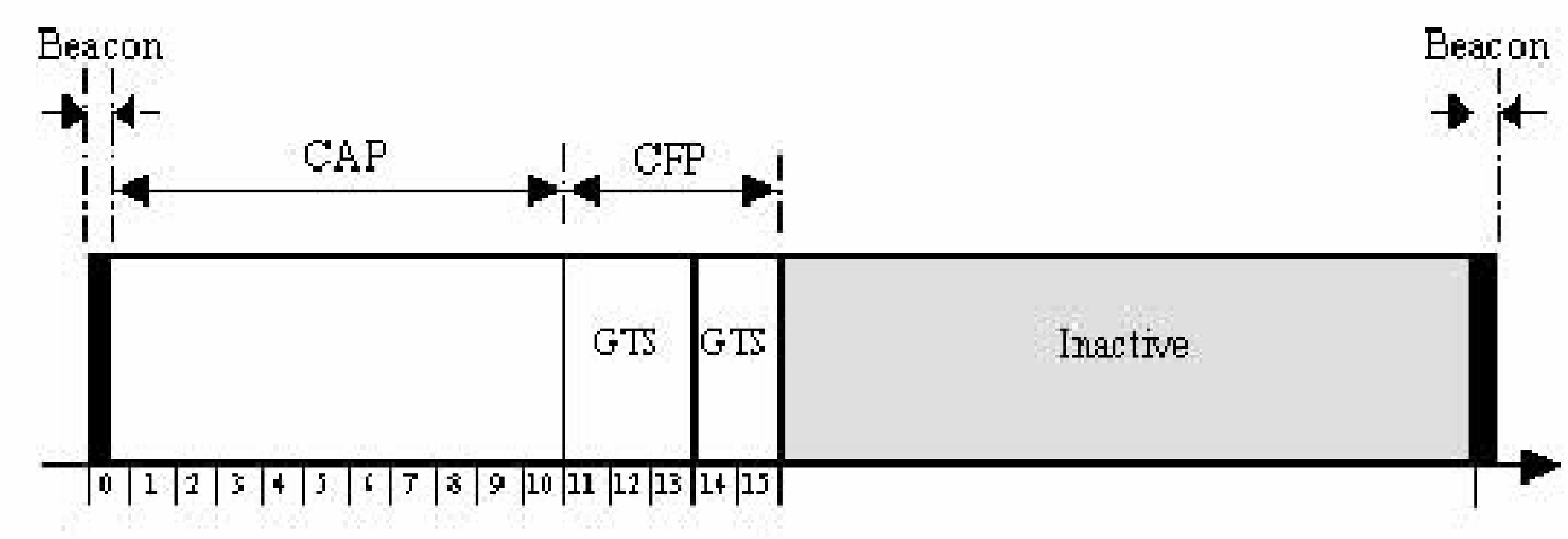


Energy-Efficient MAC Design

- ZigBee (Cont.)
  - Three devices specified
    - Network Coordinator
    - Full Function Device (FFD)
      - Can talk to any device, more computing power
    - Reduced Function Device (RFD)
      - Can only talk to a FFD, simple for energy conservation
  - CSMA/CA with optional ACKs on data packets
  - Optional beacons with superframes
  - Optional guaranteed time slots (GTS), which supports contention-free access

Energy-Efficient MAC Design

- ZigBee (Cont.)
  - Low power, low rate (250kbps) at physical layer
  - MAC layer supports low duty cycle operation
    - Target node life time > 1 year



Case Study: S-MAC

- S-MAC — by Ye, Heidemann and Estrin
- Tradeoffs

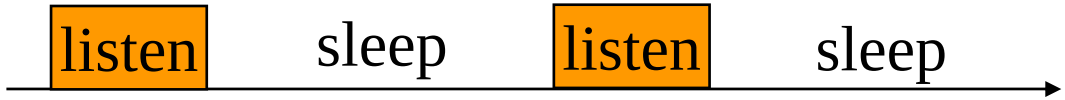
Latency
Fairness

Energy

- Major components in S-MAC
  - Periodic listen and sleep
  - Collision avoidance
  - Overhearing avoidance
  - Massage passing

Coordinated Sleeping

- Problem: Idle listening consumes significant energy
- Solution: Periodic listen and sleep

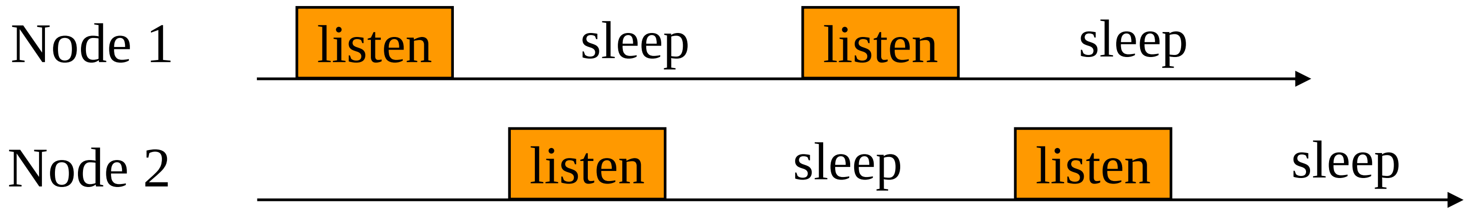


- Turn off radio when sleeping
- Reduce duty cycle to ~ 10% (120ms on/1.2s off)

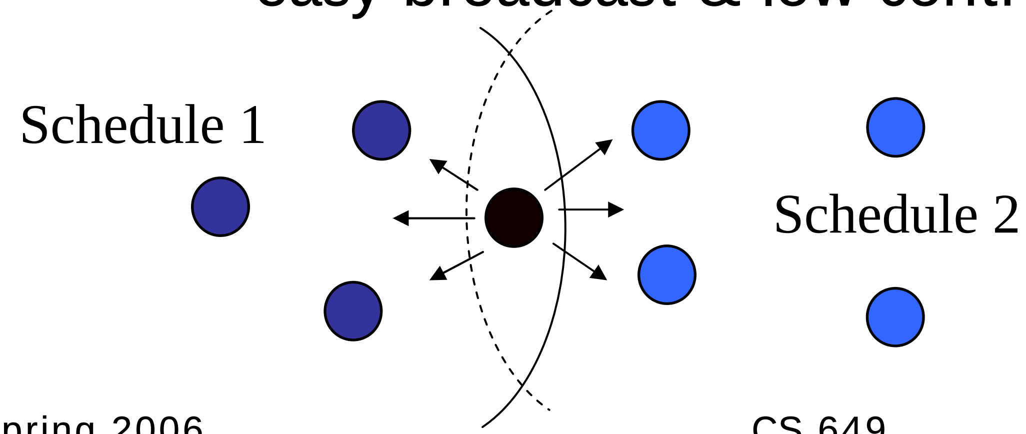
Latency  Energy

Coordinated Sleeping

- Schedules can differ



- *Prefer* neighboring nodes have same schedule
  — easy broadcast & low control overhead



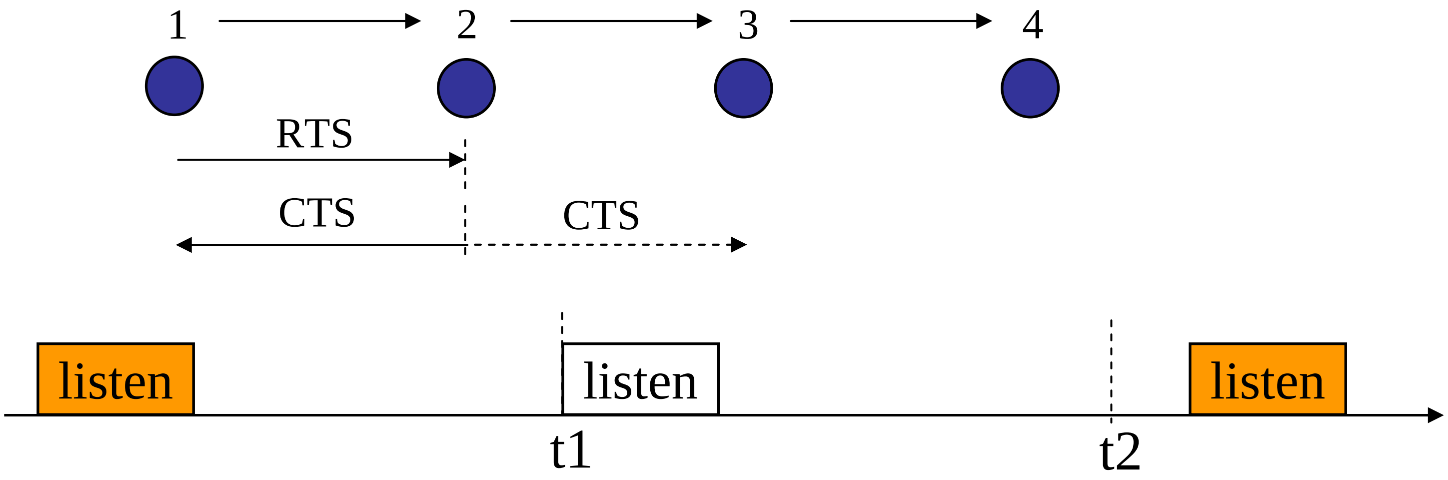
Border nodes:
two schedules

Coordinated Sleeping

- Schedule Synchronization
  - New node tries to follow an existing schedule
  - Remember neighbors' schedules
    — to know when to send to them
  - Each node broadcasts its schedule every few periods of sleeping and listening
  - Re-sync when receiving a schedule update
- Periodic neighbor discovery
  - Keep awake in a full sync interval over long periods

Coordinated Sleeping

- Adaptive listening
  - Reduce multi-hop latency due to periodic sleep
  - Wake up for a short period of time at end of each transmission



- Reduce latency by at least half

Collision Avoidance

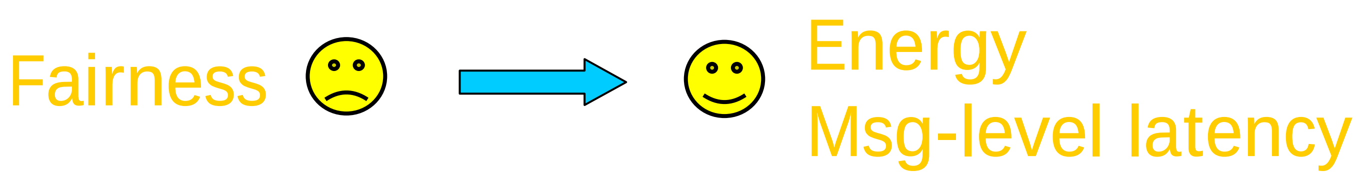
- S-MAC is based on contention
- Similar to IEEE 802.11 ad hoc mode (DCF)
  - Physical and virtual carrier sense
  - Randomized backoff time
  - RTS/CTS for hidden terminal problem
  - RTS/CTS/DATA/ACK sequence

Overhearing Avoidance

- Problem: Receive packets destined to others
- Solution: Sleep when neighbors talk
  - Basic idea from PAMAS (Singh, Raghavendra 1998)
  - But we only use in-channel signaling
- Who should sleep?
  - All immediate neighbors of sender and receiver
- How long to sleep?
  - The duration field in each packet informs other nodes the sleep interval

Message Passing

- Problem: Sensor net in-network processing requires *entire* message
- Solution: Don't interleave different messages
  - Long message is fragmented & sent in burst
  - RTS/CTS reserve medium for entire message
  - Fragment-level error recovery — ACK
    — extend Tx time and re-transmit immediately
- Other nodes sleep for whole message time

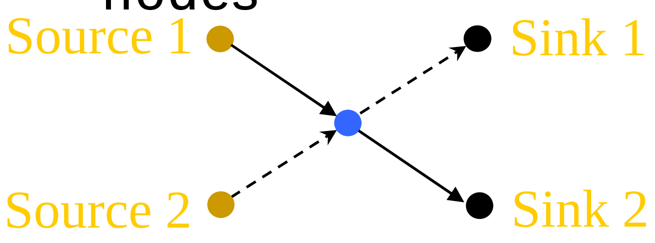


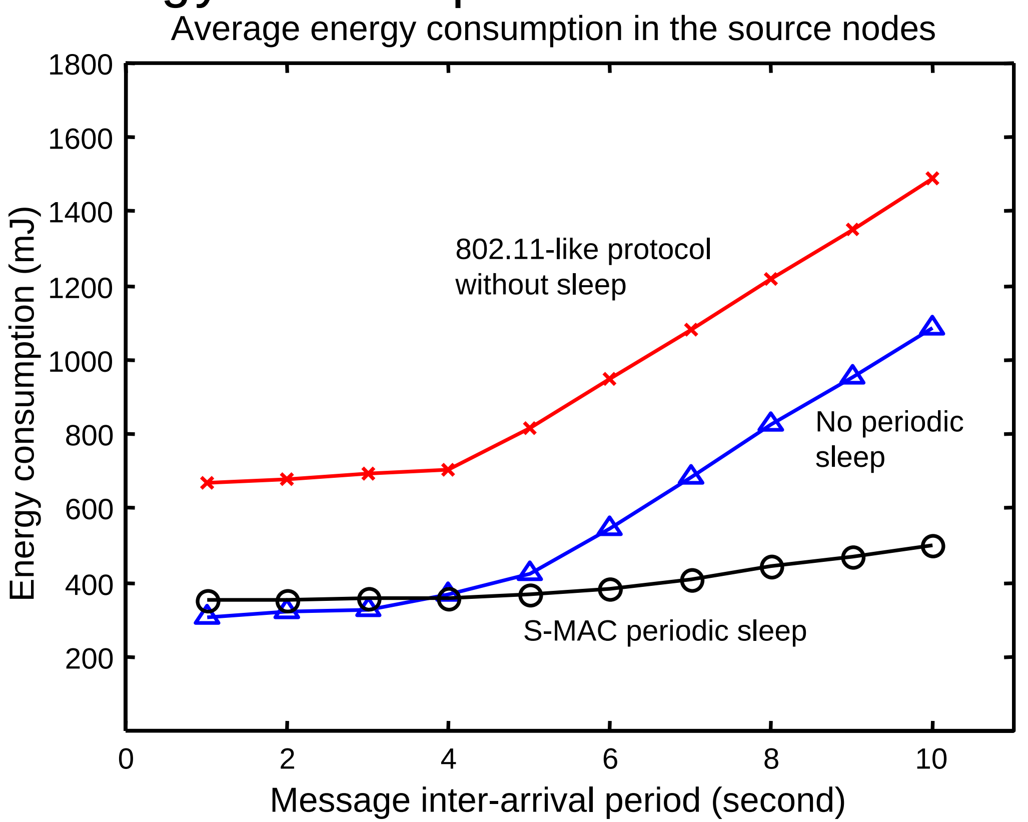
Implementation on Testbed Nodes

- Platform
  - Mica Motes (UC Berkeley)
    - 20Kbps radio at 433MHz
- Configurable S-MAC options
  - Low duty cycle with adaptive listen
  - Low duty cycle without adaptive listen
  - Fully active mode (no periodic sleeping)

Experiments: two-hop network

- Topology and measured energy consumption on source nodes



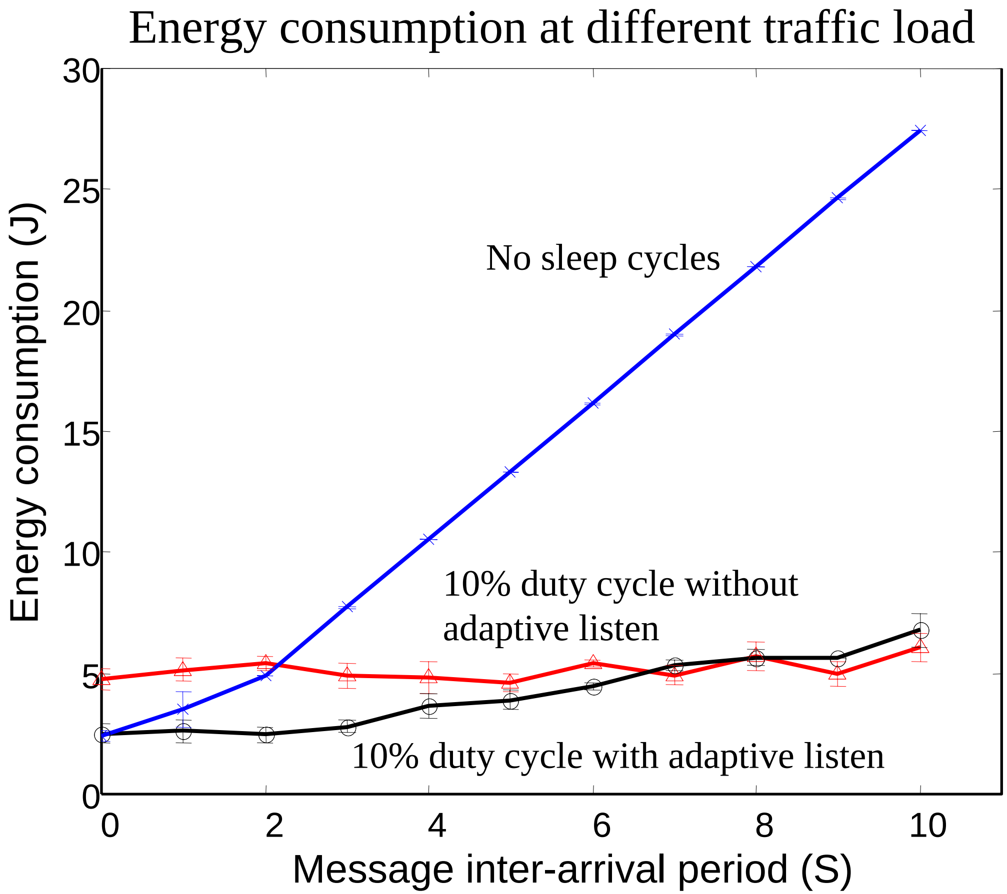


- S-MAC consumes much less energy than 802.11-like protocol w/o sleeping
- At heavy load, overhearing avoidance is the major factor in energy savings
- At light load, periodic sleeping plays the key role

Energy Consumption over Multi-Hops

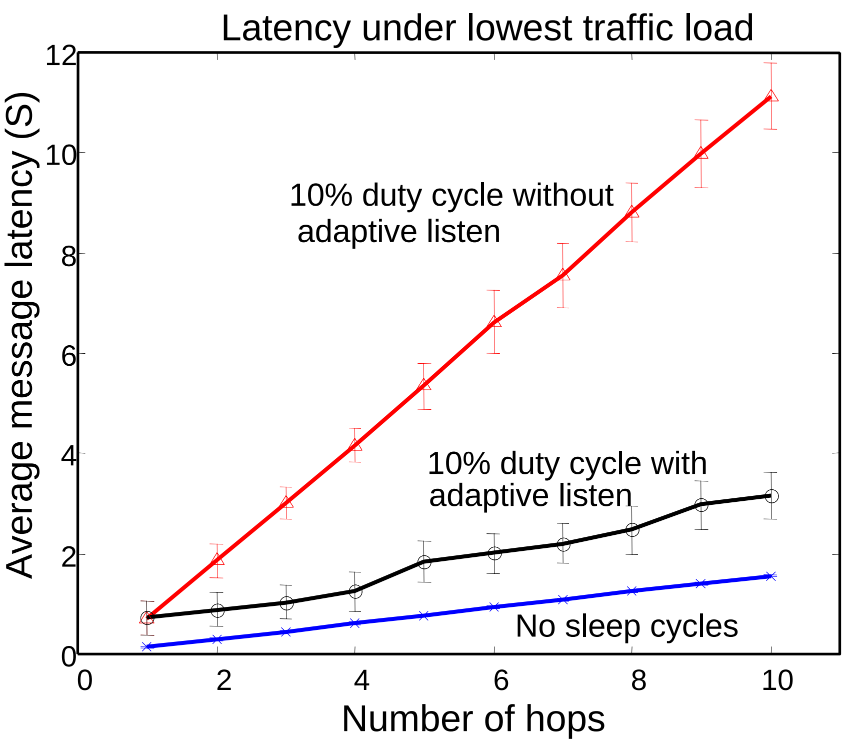
- Ten-hop linear network at different traffic load

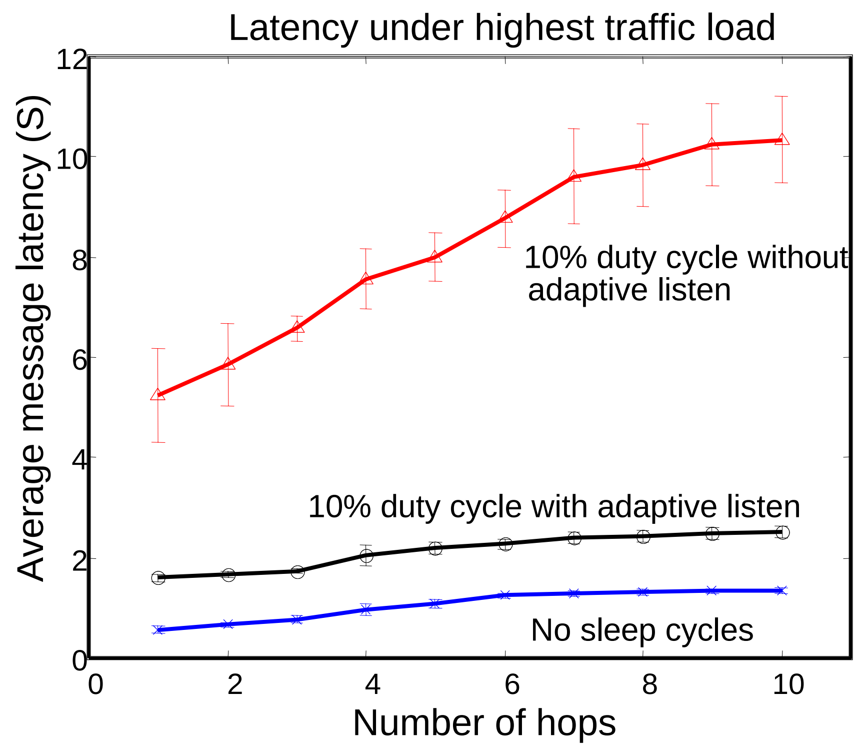
- 3 configurations of S-MAC
- At light traffic load, periodic sleeping has significant energy savings over fully active mode
- Adaptive listen saves more at heavy load by reducing latency



Latency as Hops Increase

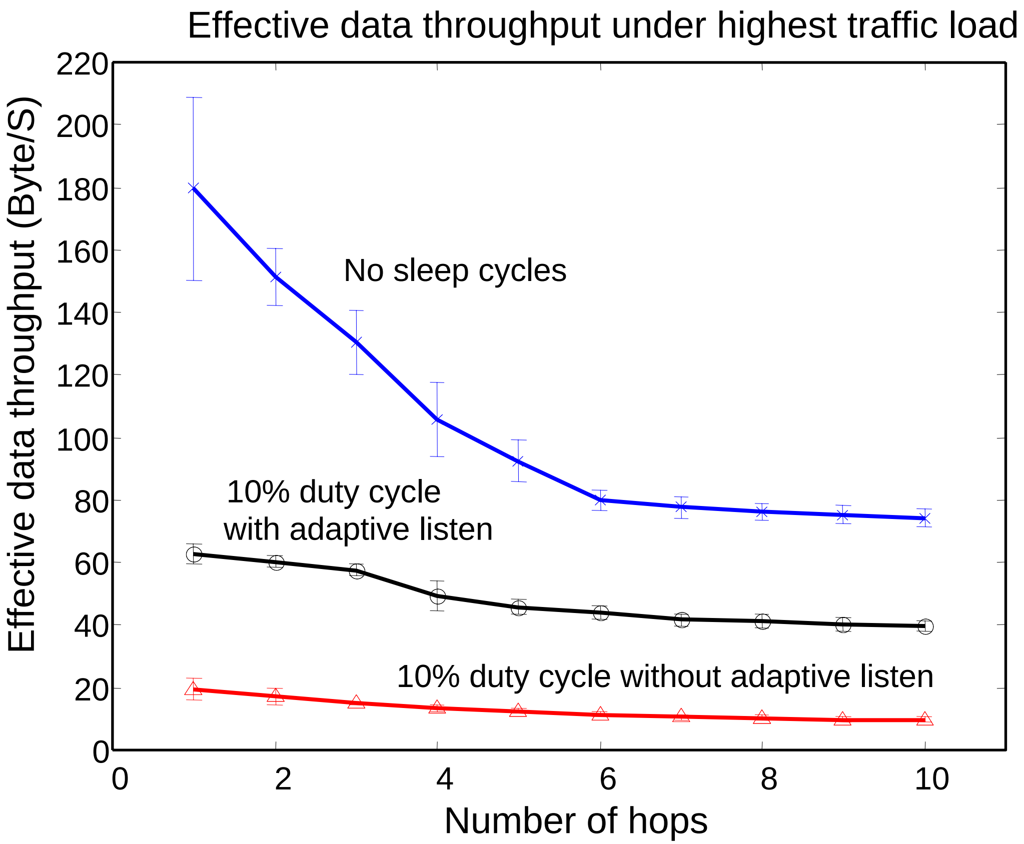
- Adaptive listen significantly reduces latency causes by periodic sleeping





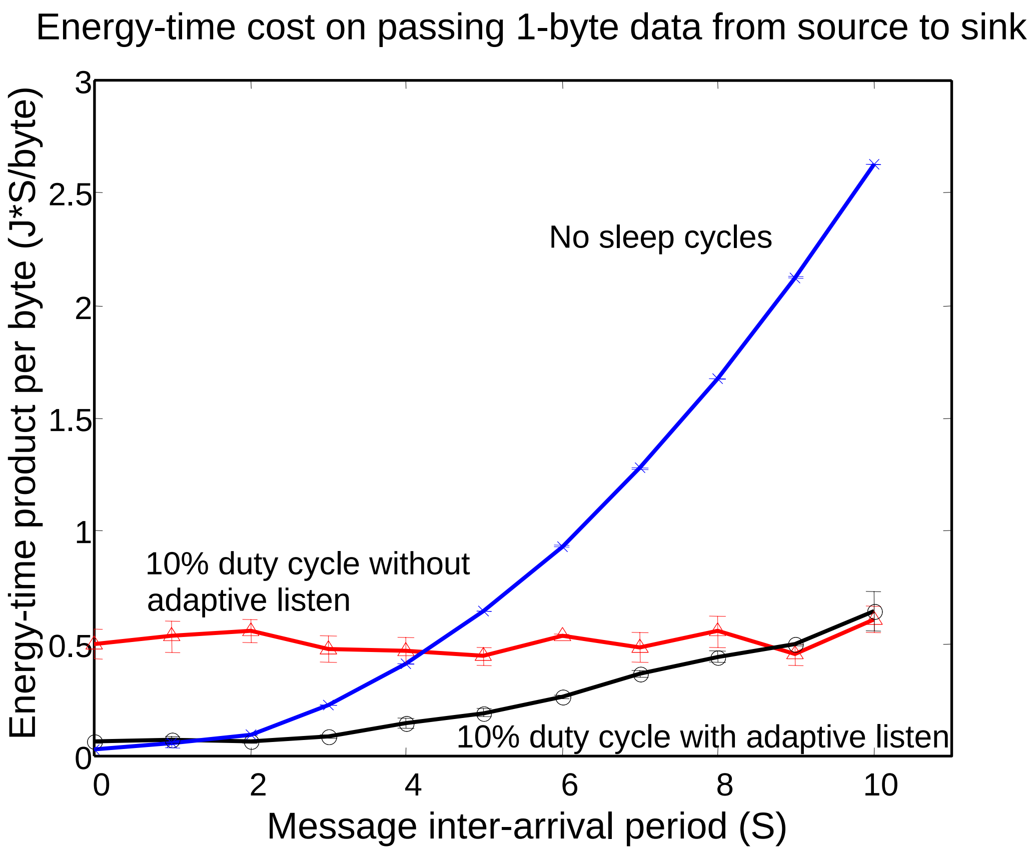
Throughput as Hops Increase

- Adaptive listen significantly increases throughput
  - Using less time to pass the same amount of data



Combined Energy and Throughput

- Periodic sleeping provides excellent performance at light traffic load
- With adaptive listening, S-MAC achieves about the same performance as no-sleep mode at heavy load



Adaptive Listen Slots

- In S-MAC all nodes have listen slots of the same duration
  - Different nodes might have different tx/rx patterns
  - Idle listening wastes power
  - Idea: adaptively change the idle listen slot

“An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks” by T. van Dam, K. Langendoen

Energy-efficient MAC protocols

WSN-specific protocols

- starting from 2000 (1 paper)
- exponential growth (2004, 16+ papers)

Classification (up to May 2004, 20 papers)

- the number of **channels** used
- the degree of **organization** between nodes
- the way in which a node is **notified** of an incoming msg

Protocol classification

Protocol	Channels	Organization	Notification
2000			
SMACS	FDMA	frames	schedule
2001			
PACT	single	frames	schedule
PicoRadio	CDMA+tone	random	wakeup
2002			
STEM	data+ctrl	random	wakeup
Preamble sampling	single	random	listening
Arisha	single	frames	schedule
S-MAC	single	slots	listening
PCM	single	random	listening
Low Power Listening	single	random	listening

Protocol classification

2003

Sift	single	random	listening
EMACs	single	frames	schedule
T-MAC	single	slots	listening
TRAMA	single	frames	schedule
WiseMAC	single	random	listening

2004

BMA	single	frames	schedule
Miller	data+tone	random	wakeup+list
DMAC	single	slots	listening
SS-TDMA	single	frames	schedule
LMAC	single	frames	listening
B-MAC	single	random	listening