Ubiquitous Networks

Media Access Control

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Goals of WSN MAC Protocols

- **MAC: Efficient sharing of communication resources**
  - When the communication channel is shared
    - Wireless networks are broadcast-based and shared (multi-access) channels
  - Common goals: throughput, latency, fairness
    - Reduce collisions, consider fairness
- **Goals of WSN MAC Protocols**
  - Energy conservation is the primary goal since
    - Energy source is battery-limited
    - Communication traffic is intermittent (i.e. nodes sleep most of time)
    - To maximize the network lifetime
  - Communication latency and throughput are the secondary goals?
  - Others: scalability, adaptability, fairness, …
    - Since all nodes cooperate for a single common task, fairness is a secondary concern as long as application-level performance is not degraded

Sources of Energy Wastes

- **Idle listening**
  - A node listens but no message appears
  - Occupies 50 ~ 100% of the energy required for packet reception
- **Over hearing**
  - A node listens to a message that is destined to another node
- **Collision: both at the sender and at the receiver**
  - At the receiver side, a node listens but cannot hear any due to collision
  - At the sender side, two nodes transmit at the same time but they must retransmit the messages later
- **Over emitting**
  - A node sends a message but the receiver is not ready
- **Control packet overhead**

Issues in WSN MAC Protocols

- **No single coordination authority as in infrastructure-based networks**
  - Fully-distributed autonomous protocol
    - MAC protocols and their setup must be autonomous and fully distributed without central coordination
  - Distributed synchronization among the sensor nodes
    - Sensor nodes need to synchronize with each other in a completely distributed manner for
      - Sender/receiver synchronization for transmission
      - Temporal ordering of detected events
      - Elimination of redundant events/messages
- **Energy conscious design**
  - Must minimize wasteful energy consumption
    - Wireless communication is the most energy-draining source
      - Communicating a single bit consumes as much power as processing 1000 instructions locally
- **Dynamic topology**
  - Must be adaptable to frequent topology changes
    - Due to power-down/up, and also due to failure and mobility

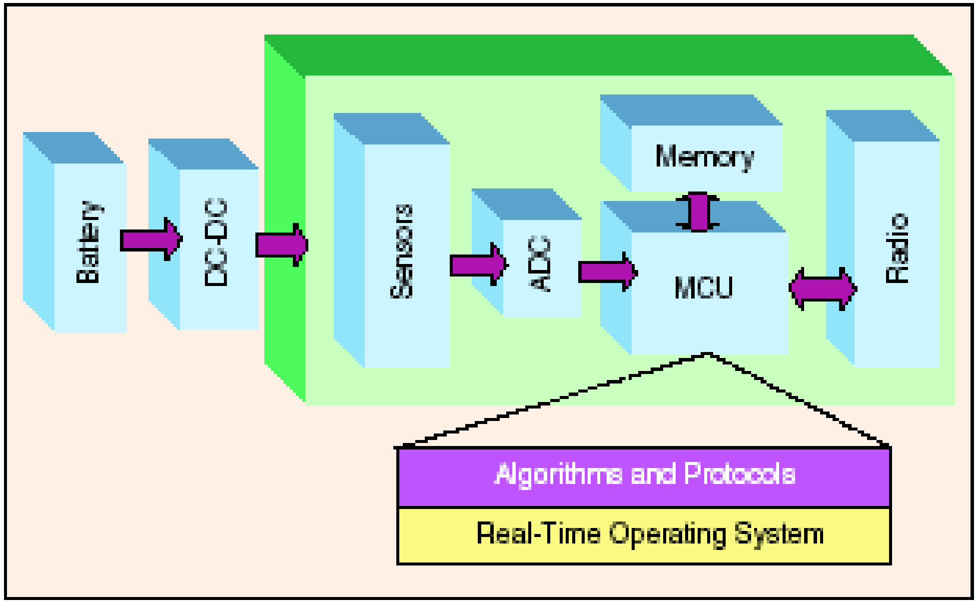
Sensor Network Traffic Patterns

Traffic patterns in sensor networks

- Little activity in lengthy period
- Intensive (burst) traffic in short time
- Highly correlated traffic
- Small packet size
- Multi-hop dynamic topologies
- The network operates as a collective structure rather than many point-to-point flows
- Converge-cast traffic
  - Many sensor nodes (sources) deliver packets to a few sink nodes

Energy Distribution

- **Radio**
  - RF transceiver
  - Power amplifier
  - Digital baseband processing
- **Processing**
  - Protocol stack
  - Applications
  - Operating system
- **Sensors & ADC**
  - Low-power modalities (temperature, light)
  - Medium-power modalities (acoustic, magnetic)
  - High-power modalities (image, video)
- **Actuators, clock distribution**



Computation versus Communication

Processing overhead

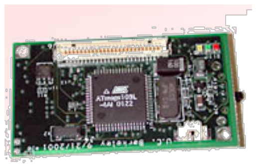
- 0.5 nJ/Instruction for Cygnal C8051F300 @ 25MHz
- 1.1 nJ/Instruction for Xscale PXA250 @ 400 MHz
- 2.1 nJ/Instruction for ARM Thumb @ 40 MHz
- 4 nJ/Instruction for ATMega128L @ 4MHz

Communication overhead

- Energy per bit in radios is a strong function of desired communication performance and choice of modulation
  - Currently around 150 nJ/bit for short ranges

MICA mote Berkeley

Transmit	**720 nJ/bit**	Processor	**4 nJ/op**
Receive	**110 nJ/bit**	**~ 100 ops/bit**	



WINS node RSC

Transmit	**6600 nJ/bit**	Processor	**1.6 nJ/op**
Receive	**3300 nJ/bit**	**~ 3000 ops/bit**	

Source: Rockwell Automation

Power Dissipation Example: WINS

- **WINS NG 2.0**
  - Development platform used in DARPA SensIT
  - SH-4 processor @ 167 MHz
  - DSP with 4-channel 16-bit ADC
  - GPS
  - dual 2.4 GHz radios
  - Linux 2.4 + Sensoria APIs
- **Power Dissipation**
  - Processor
    - Active = 360 mW (repeated tx/rx)
    - Sleep = 41 mW
    - Off = 0.9 mW
  - Sensor = 23 mW
  - Tx = 700mW max
  - Rx = 368mW

Table 1. Power Analysis of Rockwell's Wins Nodes.

MCU Mode	Sensor Mode	Radio Mode	Power (mW)
Active	On	Tx (Power: 36.3 mW)	1080.5
		Tx (Power: 19.1 mW)	986.0
		Tx (Power: 13.8 mW)	942.6
		Tx (Power: 3.47 mW)	815.5
		Tx (Power: 2.51 mW)	807.5
		Tx (Power: 0.96 mW)	787.5
		Tx (Power: 0.30 mW)	773.9
		Tx (Power: 0.12 mW)	771.1
Active	On	Rx	751.6
Active	On	Idle	727.5
Active	On	Sleep	416.3
Active	On	Removed	383.3
Sleep	On	Removed	64.0
Active	Removed	Removed	360.0

Power Dissipation Example: Medusa II

- **UCLA Medusa MK-II**
  - ATMEL 8b CPU @ 4MHz
  - ARM Thumb 40MHz
  - 1MB FLASH, 136KB SRAM
  - TR1000 radio with 20m transmission range and up to 19.2Kbps
- **Power Dissipation**
  - Processor
    - Active ≈ 5 mW
    - Idle = 1.2 mW
    - Sleep = 0.02mW
  - Sensor ≈ 4.7 mW
  - Tx = 14.9mW max
  - Rx = 12.5mW

Table 2. Power Analysis of Medusa II Nodes.

MCU Mode	Sensor Mode	Radio Mode	Mod. Scheme	Data Rate	Power (mW)
Active	On	Tx(Power: 0.7368 mW)	OOK	2.4 kb/s	24.58
		Tx(Power: 0.0979 mW)	OOK	2.4 kb/s	19.24
		Tx(Power: 0.7368 mW)	OOK	19.2 kb/s	25.37
		Tx(Power: 0.0979 mW)	OOK	19.2 kb/s	20.05
		Tx(Power: 0.7368 mW)	ASK	2.4 kb/s	26.55
		Tx(Power: 0.0979 mW)	ASK	2.4 kb/s	21.26
		Tx(Power: 0.7368 mW)	ASK	19.2 kb/s	27.46
		Tx(Power: 0.0979 mW)	ASK	19.2 kb/s	22.06
Active	On	Rx	Any	Any	22.20
Active	On	Idle	Any	Any	22.06
Active	On	Off	Any	Any	9.72
Idle	On	Off	Any	Any	5.92
Sleep	Off	Off	Any	Any	0.02

Observations

- **Sensor node power consumption is strongly dependent on the operating mode**
  - In Medusa II, Tx : Rx : Sleep = 25mW : 22mW : 0.02mW
  - In WINS, Tx : Rx : Sleep = 1080mW : 750mW : 64mW
- **Idle radio consumes almost as much power as radio in Rx mode**
  - Radio needs to be completely shut off to save power as in sensor networks idle time dominates
- **Processing power is fairly significant (~30% of overall power)**

Observations

- **Technology trends**
  - Radios benefit less from technology improvements than processors
  - The relative impact of the communication subsystem on the system energy consumption will grow
- **Power management priority**
  - Communication is the most dominant factor
  - Processing and sensing energy in general less important for low-cost sensors
- **Using low-power components and trading-off unnecessary performance can have substantial impact on battery life and energy savings**

Power versus WSN Lifetime

MiCA Mote example

- With 2 1.5V AA batteries
  - MICA mote can last 13.2 days @ 25mW (full Tx/Rx)
  - MICA mote can last 330 days @ 1mW
- For 5 years' of sensor network lifetime, the power consumption must be reduced to 180μW

Power Management in WSN Platform

- **Processor**
  - Power saving modes: Active, Idle/Doze, Sleep states
  - Dynamic scaling of frequency, supply voltage, and threshold voltage
  - Other pure HW techniques
    - Transistor sizing: reduce dynamic power by reducing the width of the transistors
    - Transistor reordering to minimize switching activity
    - Low Power Flip-Flop
    - Clock Gating
- **Operating System**
  - The above HW knobs must be incorporated into sensor node OS
    - PA-eCos by UCLA & UCI has rate-monotonic scheduler with shutdown and DVS
  - Predictive approaches
    - Predict computation load and set voltage/frequency accordingly
- **Gains of 2x-4x typically in CPU power with typical workloads**

Power Management in WSN Protocols

- **Physical**
  - Vary modulation & error coding to find minimum energy consumption point
- **MAC**
  - Periodic sleep and wakeup (duty-cycle) to prolong the lifetime of the network
    - S-MAC, Wise-MAC, TDMA-based schemes
  - Vary transmission power to reduce energy consumption
    - Use minimum power (rather than peak power) to reach the destination
    - Use multiple short transmission instead of a single long transmission
- **Routing and topology management**
  - Uniform energy distribution among the sensor nodes
    - Sensor nodes around a sink become bottlenecks
    - Energy-aware routing schemes for static sinks and mobile sinks
- **Higher layers**
  - Data aggregation and compression

Low Power MAC Approaches

- **Static channel allocation protocols**
  - Static allocation of the channel through a predetermined assignment: such as FDMA/TDMA/CDMA
  - Plus
    - Can provide a bounded delay
  - Minus
    - Inefficient in case of variable rate traffic
      - None of the traditional static allocation methods work well with data traffic which tends to be burst
  - Example
    - SMACS (UCLA, IEEE Personal Communications, 2000)
    - DTROC (Distributed TDMA receiver oriented channel assignment) MAC protocol
- **Dynamic channel allocation protocols**
  - On-demand allocation of the channel
    - Either by a reservation or by a contention
      - Reservation-based protocols (also called demand-based protocols)
      - Contention-based protocols (also called random-access based protocols)
  - Plus
    - Efficient in case of variable rate traffic
    - Effective for sensor networks with mobile nodes

Low Power MAC Approaches

- **Reservation-based protocols**
  - Reserve the channel according to the demand
  - Minus: additional overhead of reservation process
    - May not be suitable for sensor networks due to their large messaging overhead, link setup delay, and unpredictable sensing events
- **Contention-based (random-access-based) protocols**
  - Random-access-based contention for transmission
  - Minus: no delay guarantees
  - Example
    - ALOHA: transmit whenever they have data. On collision, wait a random amount of time and retransmit
      - Pure ALOHA, slotted ALOHA
    - CSMA: transmit when they have data and *channel is not busy*
      - CSMA-CD: abort transmission as soon as they detect a collision
      - A variation of this called CSMA-CA is used in WLAN
  - S-MAC, T-MAC: derived from WLAN
  - B-MAC, WiseMAC: CSMA with preamble sampling