CMPE 58C - Wireless Sensor Networks

MAC Layer
Shared Medium Access & Sleep Scheduling
Contents

- Medium Access Control
- Evolution of MAC in Wireless Networks
- MAC Design Space in WSNs
- Energy Efficiency – Sleep Scheduling
- Taxonomy
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  - Slotted Protocols
  - Schedule Based Protocols
- Current Trends
  - Hybrid Protocols
  - IEEE 802.15.4
References

• Based on the material from
  
  
  
Part 1

General Perspective
Medium Access Control

- Control access to the “shared” medium (radio channel)
  - when to send a packet, when to listen for a packet
  - avoid interference between transmissions
  - mitigate effects of collisions (retransmit or leave to upper layers)
# Requirements in WSNs

<table>
<thead>
<tr>
<th>Requirements/Objectives</th>
<th>Wireless Networks</th>
<th>WSNs</th>
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Brief Historic Perspective

Evolution of MAC in Wireless Networks

• Since 1970s,

• increased activity since late 1990s after the successful introduction of W-LAN

• Contention Based Protocols
  - Aloha
  - CSMA
  - MACA
  - IEEE 802.11

• Schedule Based Protocols
  - TDMA
Aloha (1970s)

• Unslotted Aloha
  - transmit a packet when it is generated
  - simple (ACK/NO ACK)
  - Poor use of channel capacity (Max. throughput 18%)

• Slotted Aloha
  - allows transmissions only in synchronized slots
  - Slightly better utilization: 35%
CSMA (1975)

- first listen to the channel for a small period
- Clear channel $\rightarrow$ transmit
- Busy channel $\rightarrow$ random back-off period
- takes some time to switch the radio from rx to tx, the CSMA method is not bullet proof and collisions can still occur
MACA - CSMA/CA (1990s)

- CSMA is fine when every node can sense each other but hidden terminal problem may occur.

- 3-way handshake (RTS/CTS/DATA)
- When 2 RTSs collide, no CTS is received, nodes back off.
MACA – CSMA/CA

• Too good to silence other nodes
  - the “exposed terminal problem”

- Adjustment: Since C does not hear CTS, can transmit
IEEE 802.11 (1999)

• Operation
  - infrastructure mode (access point)
  - ad-hoc mode

• Protocol
  - DCF: Distributed Coordination Function
    • carrier sense
    • collision avoidance
  - PCF: Point Coordination Function
    • Access point polls the data
• Network Allocation Vector (NAV) - virtual carrier sensing
  - collision avoidance
  - overhearing avoidance: other nodes may sleep and wake up when a transmission is finished
Schedule based - TDMA: Spatial TDMA (1985)

- Communication is scheduled in advance
  - no contention
  - no overhearing
  - support for delay-bound traffic (voice)

- Time-Division Multiple Access
  - time is divided into slotted frames
  - access point broadcasts schedule
TDMA

- Typical WLAN setup
  - no direct communication between nodes
  - access point broadcast Traffic Control (TC) map
  - (new) nodes signal needs in Contention Period (CP)
MAC Design Space in WSNs
- WSN Characteristics
- Energy Efficiency
Characteristics

- Hardware characteristics
- Communication patterns
- Other services expected from MAC
- Energy efficiency
## Hardware Characteristics

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<td></td>
<td>8 KB Flash</td>
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<td><strong>Radio</strong></td>
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<td>CC1000</td>
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<td></td>
<td>10 Kbps</td>
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<td></td>
<td>2 μW sleep</td>
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<td>60 μW sleep</td>
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<tr>
<td></td>
<td>12 mW receive</td>
<td>36 mW receive</td>
<td>63 mW receive</td>
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<tr>
<td></td>
<td>36 mW xmit</td>
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<tr>
<td></td>
<td>0.5 ms setup</td>
<td>2 ms setup</td>
<td>1 ms setup</td>
<td></td>
</tr>
</tbody>
</table>

Energy in sending and receiving is 2-3 orders of magnitude higher than sleeping.
Communication Patterns

• **Convergecast**: Many to one
  - Increased overhead to repeat the messages
  - Bottleneck around the sink

• **Local gossip**
  - In-network processing

• **Flooding**
  - One-to-many
  - Code update, Bug fix
Other Services

Cross-Layer Optimization

• Feedback to
  - Localization
  - Time synchronization

• Routing Layer
  - Neighbor discovery
  - Network topology

• Since MAC is on top of physical layer, can provide these at no cost

  Exact moment of transmission

  Nodes in the range?
Energy Efficiency
Sleep Scheduling Techniques
Part 3
Energy Efficiency

- Transmissions are costly
- Receiving about as expensive as transmitting (sometimes higher)
- Idling can be cheaper but is still expensive

<table>
<thead>
<tr>
<th>CC2420</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep: 60 micro-watt.</td>
</tr>
<tr>
<td>Receive: 63 mW</td>
</tr>
<tr>
<td>Transmit: 57 mW</td>
</tr>
</tbody>
</table>
Sources of energy consumption/overhead

• Idle listening
  - Listening to receive possible traffic

• Collisions

• Overhearing
  - Receiving packets not intended to itself, problem in dense deployments

• Overemitting
  - Transmitting when the receiver is not ready

• Protocols overhead
  - Beacons, control packets, MAC headers

• Traffic fluctuations
  - Bursty traffic
Energy efficiency in traditional protocols?

- **IEEE 802.11**
  - Nodes inform the access point (AP) when they wish to enter sleep mode (infrastructure mode)

- **PAMAS in MACA**
  - 2 radios on a node
  - RTS/CTS signaling is carried out on a separate radio channel: prevents the collisions of larger data messages
  - Receiver sends a busy tone on the control channel to prevent others to transmit on data channel
  - Go to sleep whenever overhear a neighbor transmitting or whenever no packet to transmit
Energy efficiency in WSNs at MAC Layer

- Sleep in the majority of the time
  - switch radio off when possible (duty cycle)
  - still ensure that a node is awake when a packet intended for it

- Asynchronous Sleep Techniques
  - Secondary Wake Up Radio
  - Low Power Listening, Preamble Sampling
  - Transmitter/receiver-initiated cycle receptions (TICER/RICER)

- Synchronous Sleep Scheduling
  - Duty Cycling
Secondary Wake Up Radio

• 2 radios on a node
• Primary radio
  - Remains asleep by default
• Low-power secondary radio
  - Wakes up the primary radio if a wakeup signal is detected
• Used in Pico Radio project
• Motivation: the secondary radio is extremely low-power
Low-power listening/preamble sampling

• Receiver periodically wakes up, senses the channel
• Transmitter sends a preamble
  - Higher level packet or long RF pulse
  - May wake up all the neighbors
• Extension in WiseMAC
  - Use of ACK messages to learn about the receivers' sampling times
  - Send just before the receiver wakes up
Synchronous Sleep Scheduling

- Periodic duty-cycled sleep schedules
- Transmitters know in advance when their intended receiver will be awake
MAC Protocols for WSNs in the literature

Part 4
MAC Protocols for WSNs

• Very active research field
  - starting from 2000 (1 paper)
  - exponential growth (2004, 16+ papers)
    • was an open field
  - today?
    • Too many
    • Should propose a novel approach and show the efficiency over all existing methods
The comparison below is according to the classification put forward in the book chapter "Energy-Efficient Medium Access Control" by K. Langendoen and G. Halkes [BibTeX]

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Year</th>
<th>Channels</th>
<th>Organization</th>
<th>Notification</th>
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</tbody>
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MAC Alphabet Soup: http://www.st.ewi.tudelft.nl/~koen/MACsoup/
Taxonomy

Random Access Protocols
- No organization in time

Slotted Access Protocols
- Organized in sleep/active slots

Schedule-based Protocols
- Organized in slots and frames, TDMA

Contention Based Protocols
Random Access Protocols

• **B-MAC**
  - J. Polastre, J. Hill, and D. Culler, Versatile low power media access for wireless sensor networks, in SenSys 2004

• **WiseMAC**
Slotted Protocols

- **S-MAC**

- **T-MAC**

- **D-MAC**
Schedule based Protocols
TDMA based (framed)

• PEDAMACS

• LMAC
  - L. van Hoesel and P. Havinga, A lightweight medium access protocol (LMAC) for wireless sensor networks, in INSS 2004.
Taxonomy for this lecture
Random Access Protocols
B-MAC (Berkeley MAC)

- Combines
  - LPL/Preamble Sampling
  - Clear Channel Assessment: optimized carrier sense
  - Acknowledgements
- Reconfigurable
- Based on CSMA, No RTS/CTS
  - CA is left to upper layers, not a part but can be added
B-MAC

- Often considered as the default WSN MAC protocol
  - Used in TinyOS 1.0 and 2.0

- Advantages
  - Simplicity, instant access, adaptability, scalability, configurability

- Disadvantages
  - No solution to hidden terminal problem
  - Long preambles
WiseMAC

- Improvement over Preamble Sampling (LPL):
  - mark sampling schedule of neighbors
  - when sending wait for right moment (short preamble)
  - account for clock drift: calculate the preamble length according to drift and sampling period
WiseMAC

• Automatic adaptation to load:
  - low -> long preambles
  - high -> short preambles

• Ineffective for broadcast traffic
Summary for Random Access Protocols

• Flexible to handle
  - Different node densities
  - Different system loads
• Dynamic changes can be accommodated
• No need for synchronization
• On the other hand,
  - Hidden terminal problem (since based on CSMA)
  - Difficult to support local broadcasts
Slotted Protocols

Part 6
Sensor MAC (S-MAC)

- Improvement over CSMA/CA
  - periodic listen and sleep
  - overhearing avoidance
  - adaptive listening
  - message passing
Sensor-MAC (S-MAC)

- Improvement over CSMA/CA
  - Idea: Switch nodes off, ensure that neighboring nodes turn on simultaneously to allow packet exchange (rendez-vous)
  - periodic listen and sleep
    - Only in these **active periods**, packet exchanges happen
    - Need to also exchange wakeup schedule between neighbors
    - When awake, essentially perform RTS/CTS
  - Use SYNCH, RTS, CTS phases
**S-MAC**

- **Fixed duty cycle**
- **Schedules are established such that neighboring nodes have synchronous sleep and listen periods.**
- **Complete cycle: Listen/Sleep → Frame**
S-MAC

Synchronization

- SYNC packets are exchanged periodically to maintain schedule synchronization.

- SYNCHRONIZATION PERIOD: Period for a node to send a SYNC packet.
- Receivers will adjust their timer counters immediately after they receive the SYNC packet.
S-MAC

Synchronization

• Virtual Clusters
  - Formed via the schedule exchanges

• New node:
  - If received a schedule from a neighbor, join this virtual cluster, follow this schedule
  - If not, randomly choose a schedule and form a virtual cluster
S-MAC
Synchronization

• What if multiple schedules are received?
  - The node on the border will follow both schedules.
  - When it broadcasts a packet, it needs to do it twice, first for nodes on schedule 1 and then for those on schedule 2.
**S-MAC**

**Collision Avoidance**

- S-MAC is based on contention, i.e., if multiple neighbors want to talk to a node at the same time, they will try to send when the node starts listening.
  - Similar to IEEE802.11, i.e. use RTS/CTS mechanism to address the hidden terminal problem
  - Perform carrier sense before initiating a transmission
S-MAC

Overhearing Avoidance

• Physical and Virtual Carrier Sensing
  - RTS/CTS messages include message transmission time including time for ACK
  - All the immediate neighbors of the sender and receiver go to sleep after they hear an RTS or CTS packet.
  - Overhearing long data packets are avoided!!
S-MAC
Adaptive Listening

• Reduce multi-hop latency due to periodic sleep
• BASIC IDEA: Let the node who overhears its neighbors transmissions wake up for a short period of time at the end of each transmission.

Both neighbors will learn about how long the transmission is from the duration field in the RTS and CTS packets.
• They are able to adaptively wake up when the transmission is over.
• Reduce latency by at least half
S-MAC
Message Passing

• Long messages are broken down into smaller packets and sent continuously once the channel is acquired by RTS/CTS handshake.
• Increases the sleep time, but leads to fairness problems.
• Other nodes sleep during the entire message time

Fairness 🙁 ➔ 🎁 Energy
Msg-level latency
Timeout-MAC (T-MAC)

- In S-MAC, active period is of constant length
- What if no traffic actually happens?
  - Nodes stay awake needlessly long
- Idea: Prematurely go back to sleep mode when no traffic has happened for a certain time (=timeout)! T-MAC
  - Adaptive duty cycle!
- One ensuing problem: Early sleeping
  - C wants to send to D, but is hindered by transmission A → B
DMAC (Data gathering MAC)

- Staggers the active times according to the level on the convergecast tree
- Receive from children, transmit to parent
  - 3-slot gap is used to prevent interference
- Uses CSMA with ACKs
DMAC (Data gathering MAC)

• Advantages
  - Addresses the latency issue

• Disadvantages
  - Suitable for convergecast, not for local gossip
  - Could not pass the simulation stage
Summary for Slotted Access Protocols

• Positives
  - Loose synchronization, scalability, adaptive duty cycling according to load

• Problems:
  - Border nodes in SMAC?
  - Varying cluster sizes
    • Large clusters reduce the nr. of nodes that follow multiple schedules but increases latency
    • No support for adaptive cluster size
Schedule Based Protocols
TDMA based (framed)
Schedule Based Protocols
TDMA based (framed)

- Collision-free
- Reduced idle listening, overhearing
  - PEDAMACS
  - LMAC
PEDAMACS (Power Efficient Delay Aware Medium Access)

• For continuous data gathering applications.

• Assumptions:
  - A single access point (AP) exists in the network and all nodes communicate with this AP.
  - AP has no energy constraints and is capable of transmitting at higher power levels when needed so that it can reach any node in the network in a single hop.
  - The sensor nodes have limited transmission power and will reach the AP using multiple hops.
PEDAMACS

• 3 major phases
  - Topology learning phase (uses CSMA)
  - Topology collection phase (uses CSMA)
  - Scheduling phase
• Followed by data collection according to the schedule
• To handle topology changes, PEDAMACS runs an adjustment procedure
PEDAMACS

• Advantages
  - Collision-free access
  - Reduces latency

• Disadvantages
  - Centralized approach
  - The assumption of sink reaching all the nodes (obstacles, multi-path effects)
  - Use of CSMA in the initialization
LMAC

Lightweight Medium Access Control

- Scheduled communication
  - Collision-free access
  - Energy efficient — easily support low duty cycles
- Time slot contents:
  - Control Message
  - Data Message; Higher protocol layer message(s)
- Synchronization is achieved in a hierarchical manner
Choosing a time slot

- Reuse of time slots after > 2 hops
- No “base station” for time slot allocation
- CM contains list of occupied time slots
  - New nodes can easily join after a frame period
Summary

• Advantages
  - Localized and adaptive timeslot selection
  - Energy efficient, lightweight

• Shortcomings
  - Dependent on the number of time slots, so to the density and connectivity of the network.
  - Not adaptive to the changing density
  - What if the network is too dense?
  - Solution:
    • A mechanism that reduces the maximal connectivity in the network.
Current Trends
Current Trends

- Hybrid Protocols
- IEEE 802.15.4 standard
Hybrid Protocols
Zebra-MAC (Z-MAC)

• Runs on top of B-MAC
• Combines TDMA and CSMA features

<table>
<thead>
<tr>
<th>CSMA</th>
<th>TDMA</th>
</tr>
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<tbody>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Pros</strong></td>
</tr>
<tr>
<td>- Simple</td>
<td>- Naturally avoids collisions</td>
</tr>
<tr>
<td>- Scalable</td>
<td></td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td><strong>Cons</strong></td>
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<tr>
<td>- Collisions due to hidden terminals</td>
<td>- Complexity of scheduling</td>
</tr>
<tr>
<td>- RTS/CTS is overhead</td>
<td>- Synchronization needed</td>
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</table>
Z-MAC

- Neighborhood discovery through ping messages containing known neighbors
- Two-hop neighborhood used as input for a scheduling algorithm (DRAND)

The Transmission Rule:
- If owner of slot
  - Take a random backoff
  - if channel is clear, transmit
- Else
  - Wait for To
  - Take a random backoff
  - if channel is clear, transmit
Z-MAC

- When a node loses too many packets
  - Broadcasts notification for high-contention mode
  - Nodes do not contend for slots owned by 2\textsuperscript{nd} hop neighbors to prevent collisions due to hidden terminal problem
  - After a timeout, it falls back to normal operation
- Very tolerant to clock drift (falls back to CSMA operation)
IEEE 802.15.4

- IEEE standard for low-rate WPAN applications
- Goals: low-to-medium bit rates, moderate delays without too stringent guarantee requirements, low energy consumption
- Physical layer
  - 20 kbps over 1 channel @ 868-868.6 MHz (Europe)
  - 40 kbps over 10 channels @ 905 - 928 MHz (USA)
  - 250 kbps over 16 channels @ 2.4 GHz (global)
- MAC protocol
  - Single channel at any one time
  - Combines contention-based and schedule-based schemes
  - Asymmetric: nodes can assume different roles
IEEE 802.15.4

- Star networks: devices (RFD) are associated with coordinators (FFD)
  - Forming a PAN, identified by a PAN identifier
- Coordinator
  - Bookkeeping of devices, address assignment, generate beacons
  - Talks to devices and peer coordinators
- Beacon-mode superframe structure
  - GTS assigned to devices upon request
Conclusions

• There is no single, best MAC protocol that outperforms all others
• MAC duty cycles radio to reduce energy consumption
  - trade-off performance (latency, throughput)
• Simplicity is important (memory footprint)
• Application specific needs are important in the design space
Papers for next week
