Principles of Wireless Sensor Networks

http://www.ee.kth.se/~carlofi/teaching/pwsn-2011/wn_course.shtml

Lecture 7
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Medium Access Control and IEEE 802.15.4

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Today's learning goals

What is the Medium Access Control (MAC)?

What are the options to design MACs?

What is the role of parallel and distributed computation?

What is the MAC of IEEE 802.15.4?
Today's lecture

- Previous lecture
  - Fast-Lipschitz optimization

- Today's lecture will focus on mechanisms
  - Medium Access Control and IEEE 802.14.5
  - Exercises in the homework where previous lectures are applied
Outline

• Definition and classification of MACs

• Design methods for MACs

• The IEEE 802.15.4 protocol
Medium Access Control - MAC

- MAC: mechanism for controlling when sending a packet and when listening for a packet

  - MAC is one of the major components for energy expenditure
  - Especially, idly waiting to receive packets wastes huge amounts of energy

- We study MAC schemes that are
  - Suitable for WSNs
  - Emphasize energy-efficient operation

- These schemes have parameters that can be optimally selected by the methods introduced in the previous lectures
Requirements for energy-efficient MAC protocols

- **Remember**
  - Transmissions are costly
  - Receiving about as expensive as transmitting
  - Idle listening is still expensive

- **Energy problems**
  - **Collisions** - wasted effort when two packets collide
  - **Overhearing** - waste effort in receiving a packet destined for another node
  - **Idle listening** - sitting idly and trying to receive when nobody is sending
  - **Protocol overhead**
Main options

Wireless medium access

Centralized

- Schedule-based
  - Fixed assignment
  - Demand assignment

- Contention-based

Distributed

- Schedule-based
  - Fixed assignment
  - Demand assignment

- Contention-based
Centralized medium access

- A central station controls when a node may access the medium
  - Example: Polling, centralized computation of Time Division Multiple Access (TDMA) schedules
  - Simple and quite efficient (e.g., no collisions), but burdens the central station

- Not feasible for non-trivial wireless network sizes

- Can be quite useful when network is somehow divided into smaller clusters
  - In each cluster medium access can be controlled centrally
Schedule- vs. contention-based MACs

- **Schedule-based MAC**
  - **A schedule** regulates which participant may use which resource at which time, TDMA component
  - Schedule can be **fixed** or computed **on demand**
    - Usually: mixed - difference fixed/on demand is one of time scales
  - **Collisions, overhearing, idle listening no issues**
  - **Time synchronization needed**

- **Contention-based protocols**
  - Based on random techniques
  - Risk of colliding packets is deliberately taken
  - Hope: coordination overhead can be saved, resulting in overall improved efficiency
  - Mechanisms to handle/reduce probability/impact of collisions required
Listen before talk (Carrier Sense Multiple Access, CSMA) -
- suffers from sender not knowing what is going on at receiver,
- might destroy packets despite first listening for a clear channel
- hidden terminal problem: a transmitter does not see another transmitter
- exposed terminal problem: a transmitter senses another transmitter, which is not causing collisions at the receiver
More complex MAC protocols

- On top of the MAC protocols we have just mentioned, other mechanisms can work
  - Duty-cycling MAC
Duty cycling MAC

- **Synchronous duty cycling** (e.g. TMAC, 2003, and SMAC, 2004)
  - Negotiation of a sleep-active schedule among the neighboring nodes.
  - The sender coordinates the neighbors’ wake up times.

- **Asynchronous duty cycling** (e.g. BMAC, 2004, and X-MAC, 2006)
  - based on preamble sampling.
  - the receiver wakes up periodically to check if there is a transmission.
  - the transmitter sends preambles by **random access** until the receiver wakes up and sends back an ACK.
Outline

• Definition and classification of MACs

• Design methods for MACs

• The IEEE 802.15.4 protocol
Duty cycling MAC design

- Distributed optimization of sleep and listening times of nodes

\[
\begin{align*}
\min_{R_l, R_s} & \quad E(R_l, R_s, c, b, \lambda) \\
\text{s.t.} & \quad D_{\text{max}}(R_l, R_s, c, b, t_{\text{max}}) \leq \tau_{\text{max}} \\
& \quad R_{\text{min}}(R_l, R_s, c, b) \geq \psi_{\text{min}},
\end{align*}
\]

- **Energy**
- **Latency**
- **Reliability**

\(\tau_{\text{max}}\) : desired probability that the delay is less than \(t_{\text{max}}\)

\(\psi_{\text{min}}\) : minimum desired probability with which a data packet should be received.
MAC design of WSNs

Model mathematically the protocol behaviour

Select the metrics (energy, delay, reliability)

Optimize (statically or on-line) the protocol parameters

A highly efficient protocol

Application requirements

Protocol parameters: MAC retransmissions, time slots, access probabilities...

Now we study the MAC of the standard IEEE 802.15.4

IEEE 802.15.4 is the de-facto reference standard for low data rate and low power WSNs

Characteristics:
- low data rate for ad hoc self-organizing network of inexpensive fixed, portable and moving devices
- high network flexibility
- very low power consumption
- low cost
Outline

• Definition and classification of MACs

• Design methods for MACs

• The IEEE 802.15.4 protocol
IEEE 802.15.4 specifies two layers

- **Physical layer**
  - 2.4Ghz global, 250Kbps
  - 915MHz America, 40Kbps
  - 868MHz Europe, 20Kbps

- **Medium Access Control (MAC) layer**

IEEE 802.15.5 does not specify the routing
IEEE 802.15.4 networks

- IEEE 802.15.4 network composed of
  - full-function device (FFD)
  - reduced-function device (RFD).
- A network includes at least one FFD
- The FFD can operate in three modes:
  - a personal area network (PAN) coordinator
  - a coordinator
  - a device
- An FFD can talk to RFDs or FFDs
- RFD can only talk to an FFD
IEEE 802.15.4 network topologies

- 3 types of topologies
  - star topology
  - peer-to-peer topology
  - cluster tree
Cluster-tree topology
IEEE 802.15.4 physical layer

- Frequency bands:
  - 2.4 - 2.4835GHz, global, 16 channels, 250Kbps
  - 902.0 - 928.0MHz, America, 10 channels, 40Kbps
  - 868 - 868.6MHz, Europe, 1 channel, 20Kbps

- Features of the PHY layer
  - activation and deactivation of the radio transceiver
  - energy detection (ED)
  - link quality indication (LQI)
  - clear channel assessment (CCA)
  - transmitting and receiving packets across the wireless channel
  - dynamic channel selection by scanning a list of channels in search of beacon, ED, LQI, and channel switching
# IEEE 802.15.4 physical layer

## 868MHz/915MHz PHY

- **Channel 0**
  - Frequency: 868 MHz

- **Channels 1-10**
  - Frequency: 868.3 MHz to 928 MHz
  - Bandwidth: 2 MHz

## 2.4 GHz PHY

- **Channels 11-26**
  - Frequency: 2.4 GHz
  - Bandwidth: 5 MHz

## Table: Spreading and Data Parameters

<table>
<thead>
<tr>
<th>PHY (MHz)</th>
<th>Frequency band (MHz)</th>
<th>Spreading parameters</th>
<th>Data parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Chip rate (kchips/s)</td>
<td>Modulation</td>
</tr>
<tr>
<td>868/915</td>
<td>868–868.6</td>
<td>300</td>
<td>BPSK</td>
</tr>
<tr>
<td></td>
<td>902–928</td>
<td>600</td>
<td>BPSK</td>
</tr>
<tr>
<td>868/915 (optional)</td>
<td>868–868.6</td>
<td>400</td>
<td>ASK</td>
</tr>
<tr>
<td></td>
<td>902–928</td>
<td>1600</td>
<td>ASK</td>
</tr>
<tr>
<td>868/915 (optional)</td>
<td>868–868.6</td>
<td>400</td>
<td>O-QPSK</td>
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<tr>
<td></td>
<td>902–928</td>
<td>1000</td>
<td>O-QPSK</td>
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<tr>
<td>2450</td>
<td>2400–2483.5</td>
<td>2000</td>
<td>O-QPSK</td>
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</table>
Physical layer data unit

<table>
<thead>
<tr>
<th>Octets</th>
<th>1</th>
<th>variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preamble</td>
<td>SFD</td>
<td>Frame length (7 bits)</td>
</tr>
<tr>
<td>SHR</td>
<td>PHR</td>
<td>PHY payload</td>
</tr>
</tbody>
</table>

The SFD indicates the end of the SHR and the start of the packet data.

PHR: PHY header
PHY payload < 128 byte
The MAC provides two services:

- data service
- management service

MAC features: beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association and disassociation.
Superframes

- Superframe structure:
  - format defined by the PAN coordinator
  - bounded by network beacons
  - divided into 16 equally sized slots

- Beacons
  - used to synchronize the attached devices, to identify the PAN and to describe the structure of superframes.
  - sent in the first slot of each superframe.
  - turned off if a coordinator does not use the superframe structure

- Superframe portions: active and an inactive
  - inactive portion: a node does not interact with its PAN and may enter a low-power mode
  - active portion: contention access period (CAP) and contention free period (CFP)
  - Any device wishing to communicate during the CAP shall compete with other devices using a slotted CSMA/CA mechanism
  - The CFP contains guaranteed time slots (GTSs).
A Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) algorithm is implemented at the MAC layer.

If a superframe structure is used in the PAN, then slotted CSMA-CA is used in the CAP period.

If beacons are not used in the PAN or a beacon cannot be located in a beacon-enabled network, unslotted CSMA-CA is used.
CSMA-CA

- Each device has 3 variables: NB, CW and BE.

- **NB**: number of times the CSMA/CA algorithm was required to backoff while attempting the current transmission.
  - It is initialized to 0 before every new transmission.

- **BE**: backoff exponent
  - how many backoff periods a device shall wait before attempting to assess the channel.

- **CW**: contention window length (used for slotted CSMA-CA),
  - Is the number of backoff periods that need to be clear of activity before the transmission can start.
  - It is initialized to 2 before each transmission attempt and reset to 2 each time the channel is assessed to be busy.
Flow diagram to Transmit a packet with CSMA/CA in Slotted and Unslotted modalities
Guarantee Time Slot (GTS) Allocation

- The GTSs always appear at the end of the active superframe starting at a slot boundary immediately following the CAP.
- The PAN coordinator may allocate up to 7 GTSs.
- A GTS can occupy more than one slot period.
- SO < 15. If SO=15, the superframe will not be active anymore after the beacon.
- BO < 15. If BO=15, the superframe is ignored.
Guaranteed Time Slots

- A GTS allows a device to operate within a portion of the superframe that is dedicated exclusively to it.
- A device attempts to allocate and use a GTS only if it is tracking the beacons.

GTS allocation:
- The management of the GTSs is undertaken by the PAN coordinator only.
- A GTS is used only for communications between the PAN coordinator and a device.
- The GTS direction is specified as either transmit or receive.
- A single GTS can extend over one or more superframe slots.

P. Park et al., ”Performance Analysis of GTS Allocation in Beacon Enabled IEEE 802.15.4”, IEEE SECON 09
Uplink MAC: beacon and non-beacon-enabled

Communication to a coordinator in a beacon-enabled network

Communication to a coordinator in non-beacon-enabled network
Downlink MAC: Beacon and non-beacon-enabled

From a coordinator in a beacon-enabled PAN

From a coordinator in a non-beacon-enabled PAN
Conclusions

- Many different ideas exist for medium access control in WSN
- Comparing their performance and suitability is difficult
- Especially: clearly identifying interdependencies between MAC protocol and other layers/applications is difficult
  - Which is the best MAC for which application?
  - Need of a “MAC engine” that optimally selects the best MAC for given conditions
Next lecture

- Friday November 11
- Today's homework due for Tuesday November 15