

Principles of Wireless Sensor Networks

<https://www.kth.se/social/course/EL2745/>

Lecture 5

Medium Access Control

Carlo Fischione

Associate Professor of Sensor Networks

e-mail: carlofi@kth.se

<http://www.ee.kth.se/~carlofi/>



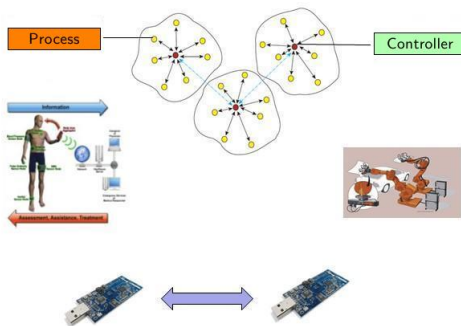
*KTH Royal Institute of Technology
Stockholm, Sweden*

September 18, 2014

Course content

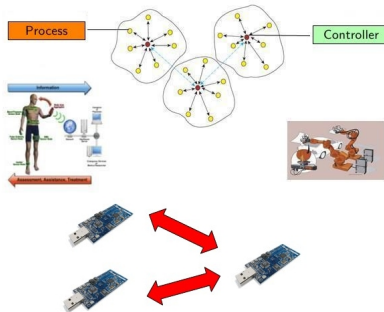
- Part 1
 - ▶ Lec 1: Introduction to WSNs
 - ▶ Lec 2: Introduction to Programming WSNs
- Part 2
 - ▶ Lec 3: Wireless Channel
 - ▶ Lec 4: Physical Layer
 - ▶ Lec 5: Medium Access Control Layer
 - ▶ Lec 6: Routing
- Part 3
 - ▶ Lec 7: Distributed Detection
 - ▶ Lec 8: Static Distributed Estimation
 - ▶ Lec 9: Dynamic Distributed Estimation
 - ▶ Lec 10: Positioning and Localization
 - ▶ Lec 11: Time Synchronization
- Part 4
 - ▶ Lec 12: Wireless Sensor Network Control Systems 1
 - ▶ Lec 13: Wireless Sensor Network Control Systems 2
 - ▶ Lec 14: Summary and Project Presentations

Previous lectures



- How information is modulated and transmitted over the wireless channel?
- What is the successful probability to receive bits?

Today's lecture



- When a node gets the right to transmit messages?
- What is the mechanism to get such a right?

Today's learning goals

- What is the Medium Access Control (MAC)?
- What are the options to design MACs?
- What is the MAC of IEEE 802.15.4?

Outline

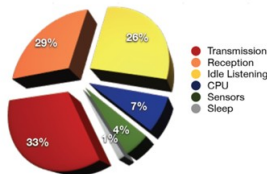
- Definition and classification of MACs
- The IEEE 802.15.4 protocol

Outline

- Definition and classification of MACs
 - ▶ TDMA, FDMA, CSMA, ALOHA
 - ▶ Hidden and exposed terminals
- The IEEE 802.15.4 protocol

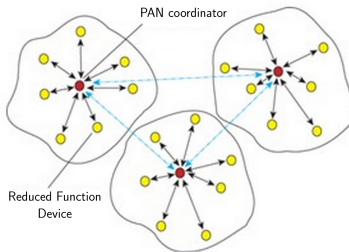
Medium Access Control - MAC

- MAC: mechanism for controlling when sending a message (packet) and when listening for a packet
- MAC is one of the major components for energy expenditure in WSNs
 - ▶ Receiving packets is about as expensive as transmitting
 - ▶ Idle listening for packets is also expensive



Typical power consumption of a node

Problems for MACs



1. Collisions: wasted effort when two messages collide
2. Overhearing: wasted effort in receiving a message destined for another node
3. Idle listening: sitting idly and trying to receive a message when nobody is sending
4. Protocol overhead



The hidden terminal problem

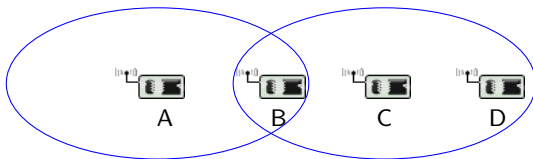
- Terminal, another word for node
- **Hidden** terminal problem:

The hidden terminal problem



- Terminal, another word for node
- **Hidden** terminal problem:

The hidden terminal problem



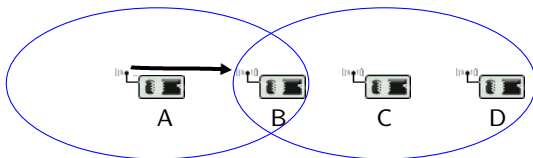
Transmit range:

(depends on the channel, transmit power,...)

distance past which the SNR is in outage

- Terminal, another word for node
- **Hidden** terminal problem:

The hidden terminal problem



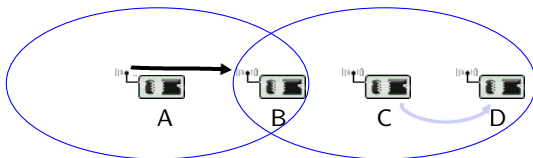
Transmit range:

(depends on the channel, transmit power,...)

distance past which the SNR is in outage

- Terminal, another word for node
- **Hidden** terminal problem:
 - ▶ Node A wants to send a message to B

The hidden terminal problem



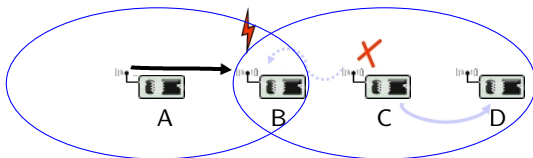
Transmit range:

(depends on the channel, transmit power,...)

distance past which the SNR is in outage

- Terminal, another word for node
- **Hidden** terminal problem:
 - ▶ Node A wants to send a message to B
 - ▶ Node C wants to send a message to D

The hidden terminal problem



Transmit range:

(depends on the channel, transmit power,...)

distance past which the SNR is in outage

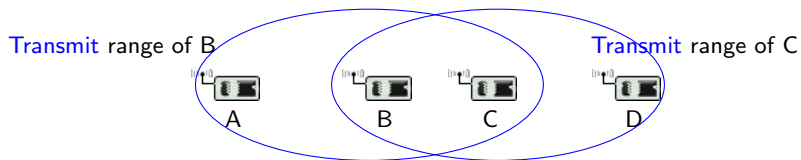
- Terminal, another word for node
- **Hidden** terminal problem:
 - ▶ Node A wants to send a message to B
 - ▶ Node C wants to send a message to D
 - ▶ Node A does not hear transmitter C sending messages that can be received by B and D

The exposed terminal problem



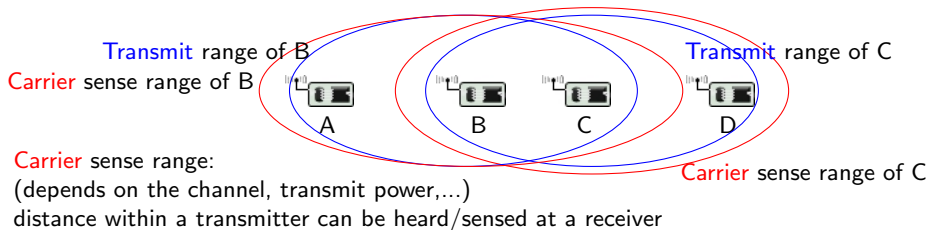
- **Exposed** terminal problem:

The exposed terminal problem



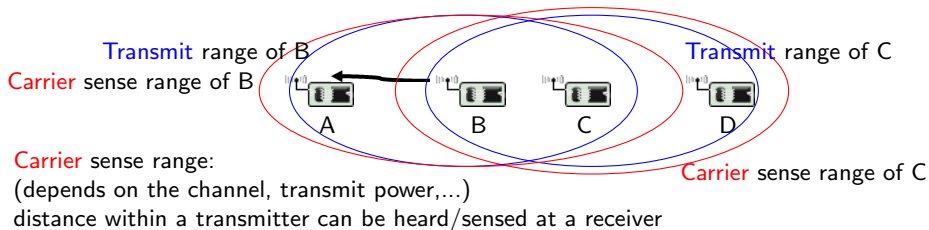
- **Exposed** terminal problem:

The exposed terminal problem



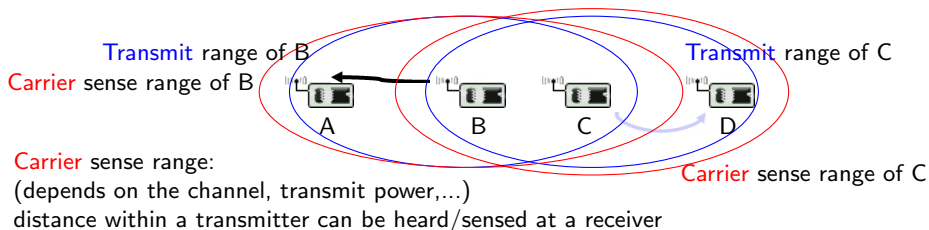
- **Exposed** terminal problem:

The exposed terminal problem



- **Exposed** terminal problem:
 - ▶ B wants to send messages to A

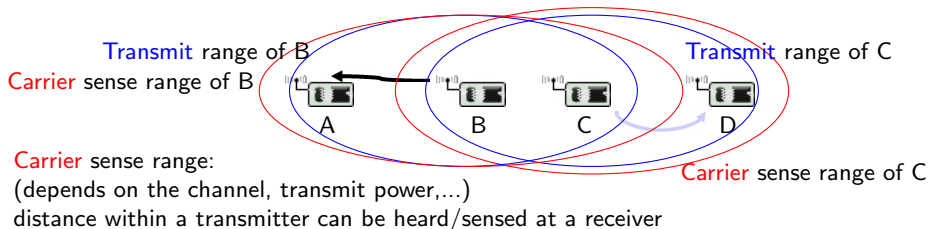
The exposed terminal problem



- **Exposed terminal problem:**

- ▶ B wants to send messages to A
- ▶ C wants to send messages to D

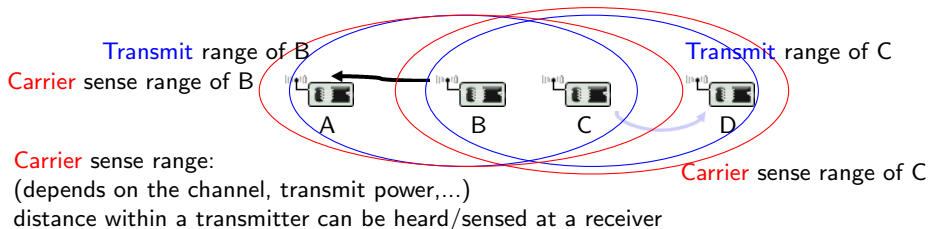
The exposed terminal problem



- **Exposed terminal problem:**

- ▶ B wants to send messages to A
- ▶ C wants to send messages to D
- ▶ Transmitter B hears transmitter C which is not causing collisions at the receiver A. A is not in the transmit range of C

The exposed terminal problem



- **Exposed terminal problem:**

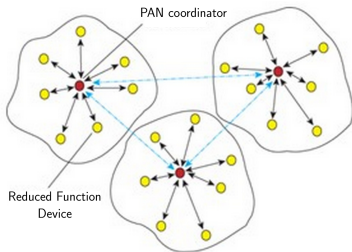
- ▶ B wants to send messages to A
- ▶ C wants to send messages to D
- ▶ Transmitter B hears transmitter C which is not causing collisions at the receiver A. A is not in the transmit range of C
- ▶ Transmitter C hears B, but D is not in the transmit range of B

Important MACs for WSNs

- TDMA - Time Division Multiple Access
 - ▶ Time is divided into time slots
 - ▶ Every node is assigned to transmit at a time slot
- FDMA - Frequency Division Multiple Access
 - ▶ As TDMA, but is the carrier frequency to be divided into slots
- CSMA - Carrier Sense Multiple Access
 - ▶ A node listens (channel assessment) if the channel is free or busy from other transmissions
 - ▶ If free, transmit the message; if busy, back-off the transmission
- ALOHA
 - ▶ If a node has a message, it draws a random variable and transmits according to the outcome

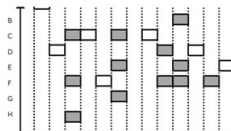
TDMA

- A central node decides the TDMA schedules
 - ▶ Simple and no packet collisions
 - ▶ Burdens the central node coordinator
 - ▶ Not feasible for large networks
- TDMA is useful when network is divided into smaller clusters
 - ▶ In each cluster, MAC can be controlled at local head



Slotted ALOHA

n number of nodes attempting to transmit



Time slots vs Node ID

- The slotted ALOHA works on top of TDMA
- Nodes are synchronized
- p probability that a node can transmit a message (because of free channel assessment)
- Probability of successful message transmission
- Probability that a slot is taken

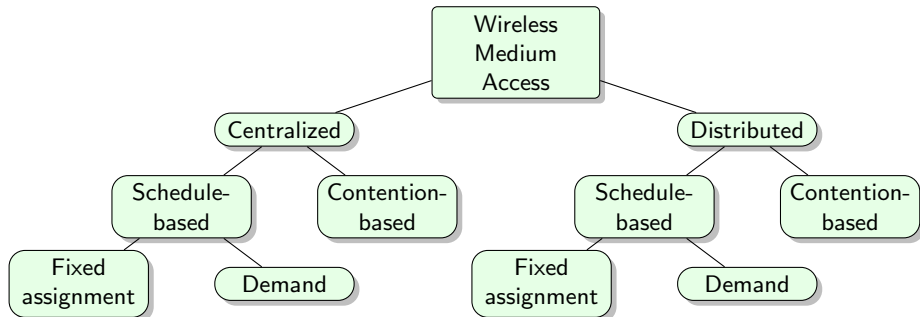
$$p(1 - p)^{n-1}$$

$$n.p(1 - p)^{n-1}$$

Schedule and contention-based MACs

- Schedule-based MACs (TDMA, FDMA)
 - ▶ A schedule regulates which node may use which slot at which time
 - ▶ Schedule can be fixed or computed on demand
 - ▶ Collisions, overhearing, idle listening no issues
 - ▶ Time synchronization needed
- Contention-based MACs (CSMA, ALHOA)
 - ▶ Based on random access
 - ▶ Risk of packet collisions
 - ▶ Mechanisms to handle/reduce probability/impact of collisions required

More in general



Outline

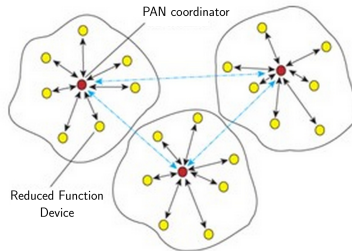
- Definition and classification of MACs
- The IEEE 802.15.4 protocol
 - ▶ Introduction
 - ▶ Physical layer
 - ▶ MAC layer

IEEE 802.15.4 protocol architecture

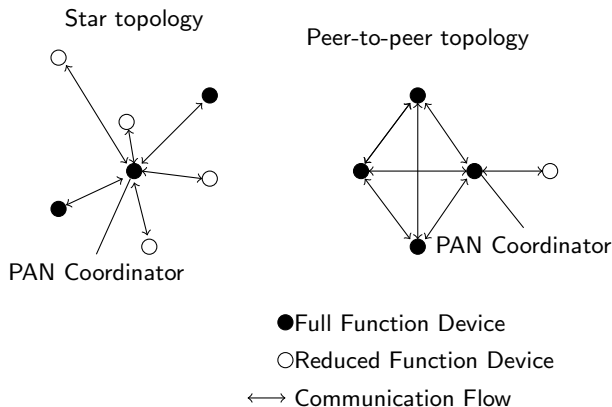
- Now we study the MAC of the standard IEEE 802.15.4
- IEEE 802.15.4 is the de-facto reference standard for low data rate and low power WSNs
- Characteristics:
 - ▶ Low data rate for ad hoc self-organizing network of inexpensive fixed, portable and moving devices
 - ▶ High network flexibility
 - ▶ Very low power consumption
 - ▶ Low cost

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



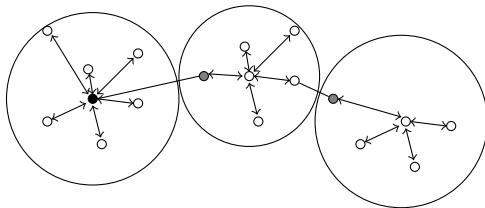
IEEE 802.15.4 network topologies



- 3 types of topologies

- ▶ Star topology
- ▶ Peer-to-peer topology
- ▶ Cluster-tree

Cluster-tree topology

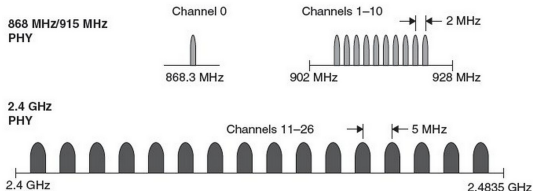


- First PAN Coordinator
- PAN Coordinator
- Device

IEEE 802.15.4 physical layer

- Frequency bands:
 - ▶ 2.4 - 2.4835GHz GHz, 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
 - ▶ Transmitting and receiving packets across the wireless channel
 - ▶ Energy detection (ED, from RSS)
 - ▶ Link quality indication (LQI)
 - ▶ Clear channel assessment (CCA)
 - ▶ Dynamic channel selection by a scanning a list of channels in search of beacon, ED, LQI, and channel switching

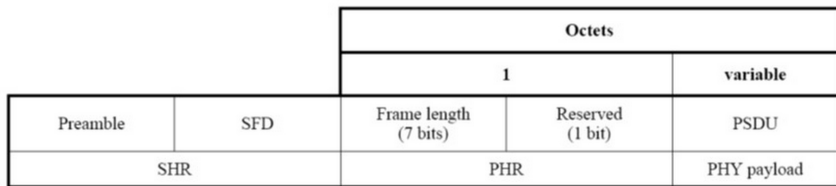
IEEE 802.15.4 physical layer



PHY (MHz)	Frequency band (MHz)	Spreading parameters		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868/915	868-868.6	300	BPSK	20	20	Binary
	902-928	600	BPSK	40	40	Binary
868/915 (optional)	868-868.6	400	ASK	250	12.5	20-bit PSSS
	902-928	1600	ASK	250	50	5-bit PSSS
868/915 (optional)	868-868.6	400	O-QPSK	100	25	16ary Orthogonal
	902-928	1000	O-QPSK	250	62.5	16ary Orthogonal
2450	2400-2483.5	2000	O-QPSK	250	62.5	16ary Orthogonal

Frequency bands and propagation parameters for IEEE 802.15.4 physical layer

Physical layer data unit

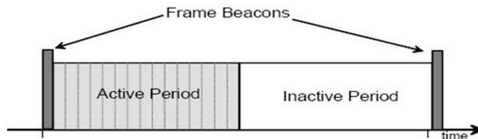


SFD indicates the end of the SHR and the start of the packet data

PHR: PHY header

PHY payload < 128 byte

IEEE 802.15.4 MAC



- 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:

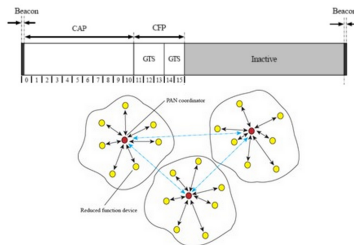
- ▶ Format defined by the PAN coordinator
- ▶ Bounded by network beacons
- ▶ Divided into 16 equally sized slots

- Beacons

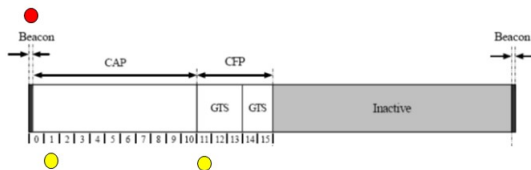
- ▶ Synchronize the attached nodes, identify the PAN and describe the structure of superframes
- ▶ Sent in the first slot of each superframe
- ▶ Turned off if a coordinator does not use the superframe structure

- 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 competes with other devices using a slotted CSMA/CA mechanism
- ▶ The CFP contains guaranteed time slots (GTSs)



IEEE 802.15.4 CSMA/CA

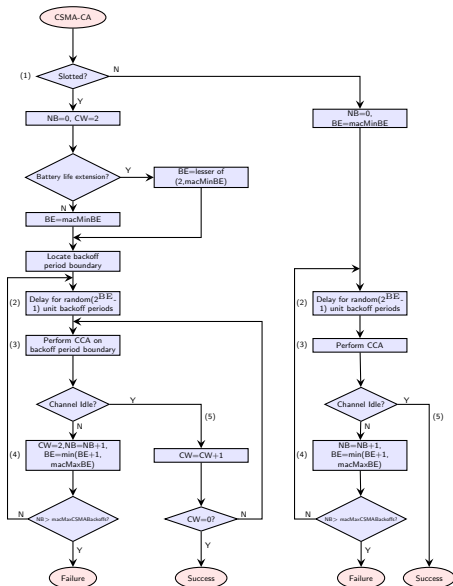


- A Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) algorithm is implemented at the MAC layer
- If a superframe structure is used in the PAN, then slotted CSMA-CA is used in the CAP period
- If beacons are not used in the PAN or a beacon cannot be located in a beacon-enabled network, unslotted CSMA-CA is used

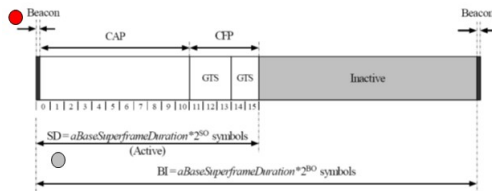
- Each device has 3 variables: NB, CW and BE
- NB: number of times the CSMA/CA algorithm was required to backoff while attempting the current transmission
 - ▶ It is initialized to 0 before every new transmission
- BE: backoff exponent
 - ▶ How many backoff periods a device shall wait before attempting 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

CSMA/CA

Flow diagram to transmit a packet with CSMA/CA in the modalities slotted (left, also called beacon modality) and unslotted (right, also called beaconless modality)



Guarantee Time Slot, GTS

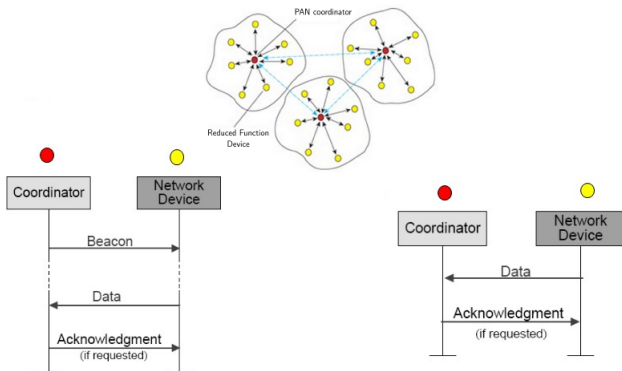


- The GTSs always appear at the end of the active superframe starting at a slot boundary immediately following the CAP
- The PAN coordinator may allocate up to 7 GTSs
- A GTS can occupy more than one slot period
- $SO < 15$. If $SO=15$, the superframe will not be active anymore after the beacon
- $BO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

GTS

- 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:
 - ▶ 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

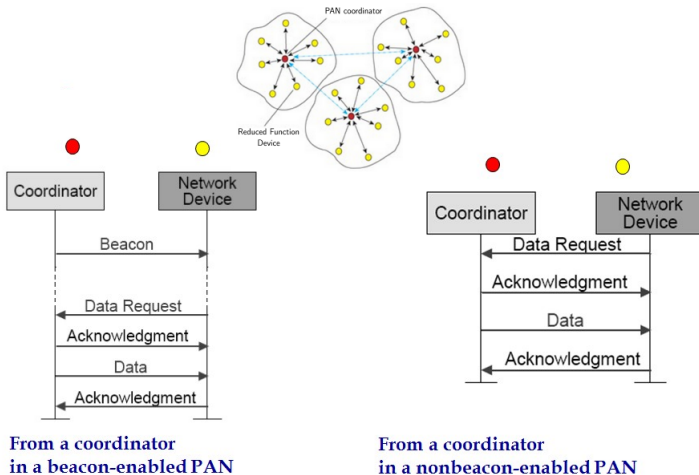
Uplink MAC: beacon and non-beacon-enabled



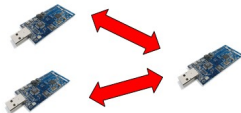
Communication to a coordinator in a beacon-enabled network

Communication to a coordinator in non-beacon-enabled network

Downlink MAC: beacon and non-beacon-enabled



Conclusions



- We have seen a MAC classification,
 - ▶ TDMA, ALOHA, CSMA
- Seen in detail the most popular protocol for WSNs, IEEE 802.15.4
- 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

- Now that we know how nodes get the right to access the wireless medium, we would like to see how a message is routed over possible paths
- Routing protocols
 - ▶ How a node decides to route a packet?
 - ▶ What are the mechanisms to get such a decision?