Principles of Wireless Sensor Networks

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Lecture 5
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Course content

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  - Lec 2: Programming
- Part 2
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  - Lec 4: Physical layer
  - Lec 5: Mac layer
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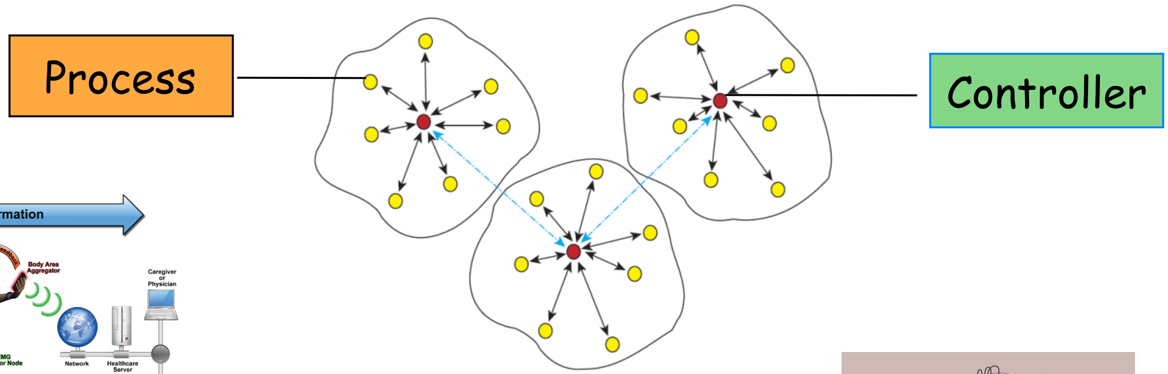
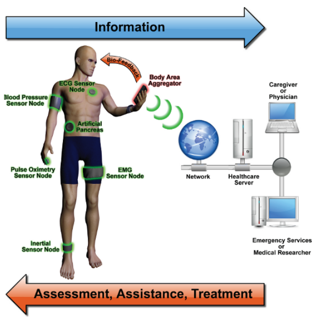
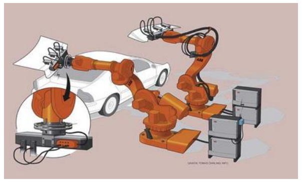
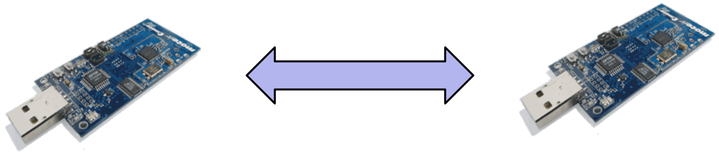
Previous lectures

Application
Presentation
Session
Transport
Routing
MAC
Phy



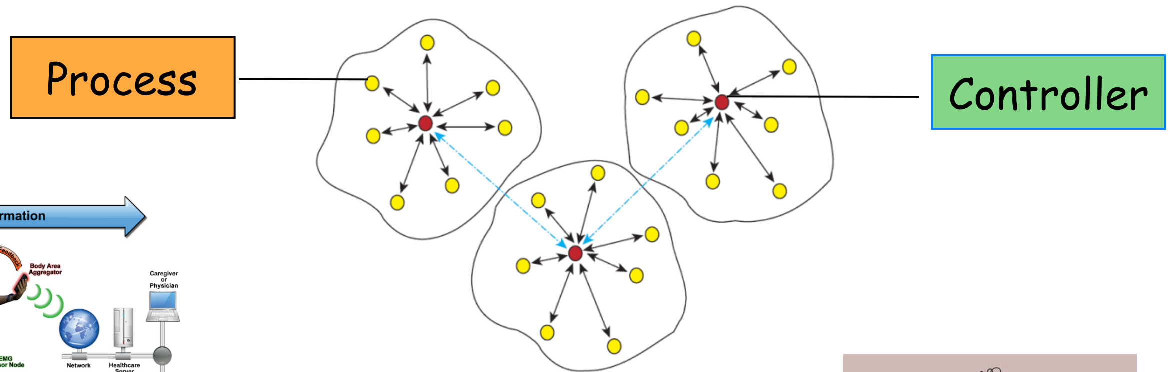


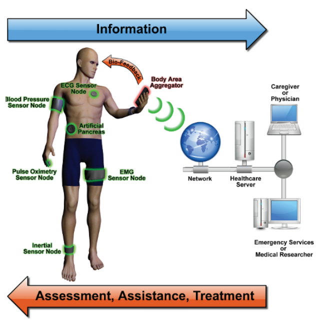


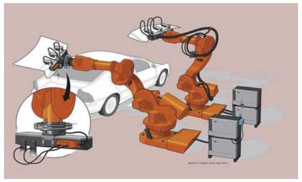


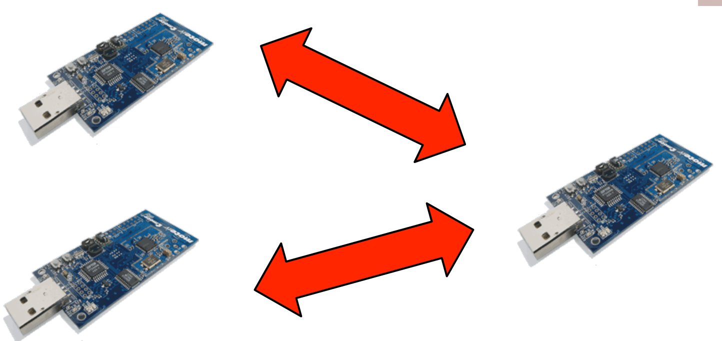
- How information is modulated and transmitted over the wireless channel?
- What is the successful probability to receive bits?

Today's lecture









- When a node gets the right to transmit messages?
- What it 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**
  - TDMA, FDMA, CSMA, ALHOA
  - Hidden and exposed terminals

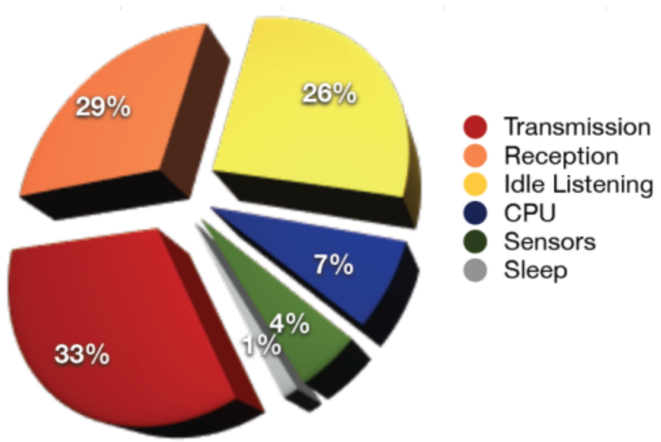
- The IEEE 802.15.4 protocol

Medium Access Control - MAC

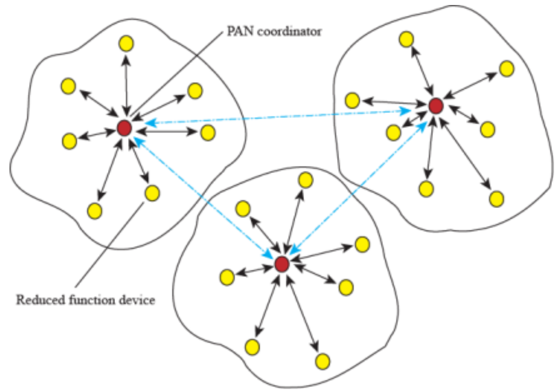
- MAC: mechanism for controlling when sending a message (packet) and when listening for a packet

- MAC is one of the major component for energy expenditure in WSNs
  - Receiving packets is about as expensive as transmitting
  - Idle listening for packets is also expensive

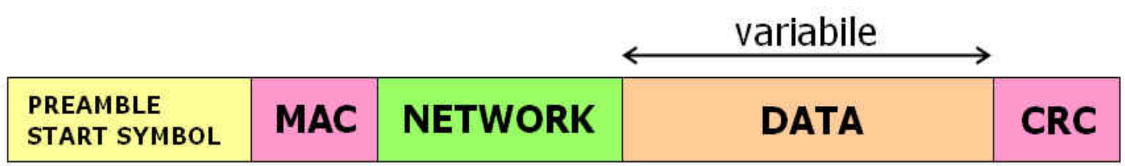
Typical power consumption of a node



Problems for MACs

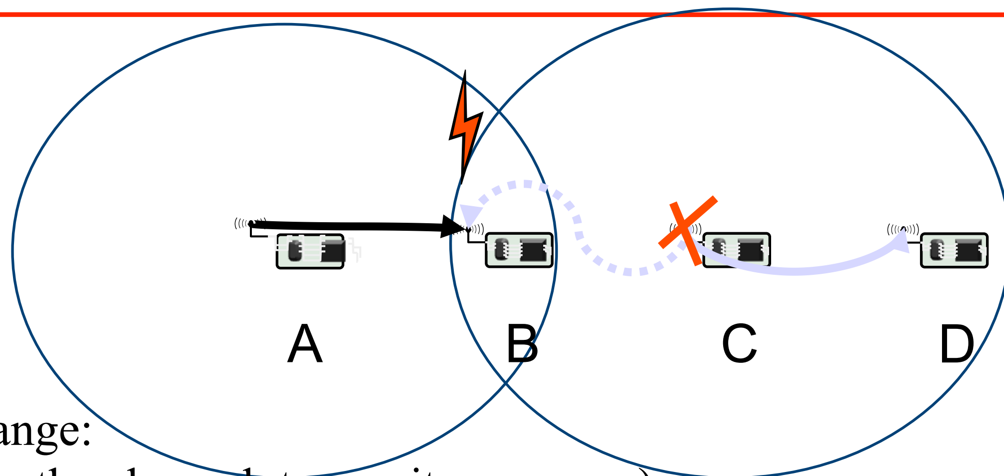


1. Collisions: wasted effort when two packets collide
2. Overhearing: waste effort in receiving a packet destined for another node
3. Idle listening: sitting idly and trying to receive when nobody is sending
4. Protocol overhead



a packet

The hidden terminal problem

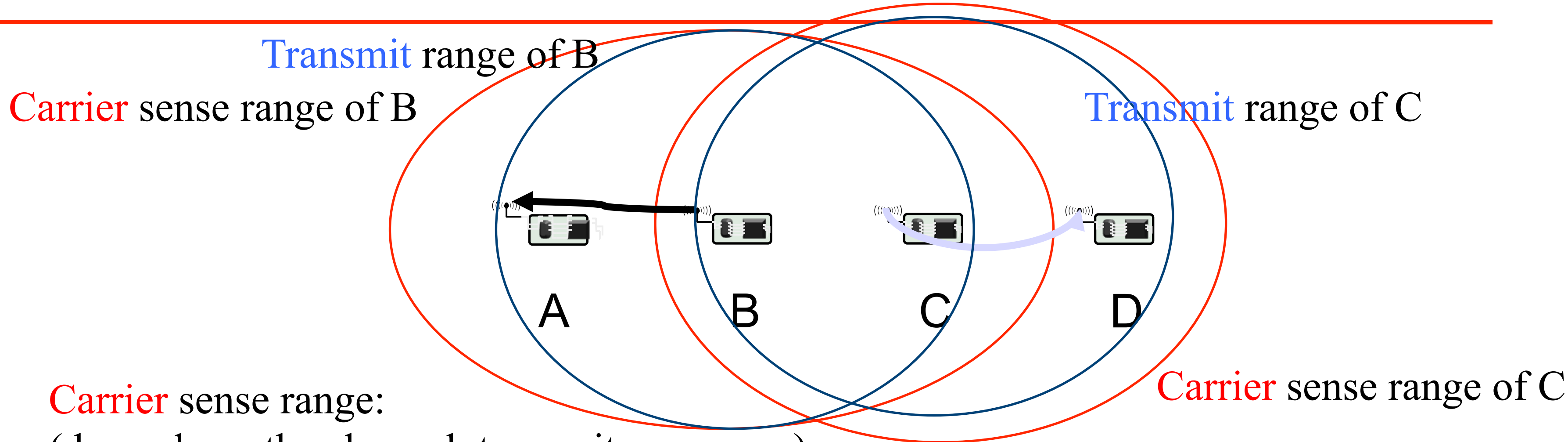


Transmit range:
(depends on the channel, transmit power, …)

distance past which the SNR is in outage

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

The exposed terminal problem



Carrier sense range:
(depends on the channel, transmit power, …)

distance within which a transmitter can be heard/sensed at a receiver

- **Exposed** terminal problem:
  - B wants to send packet to A
  - C wants to send packets 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 if free or busy from other transmissions
  - If free, transmit the packet; if busy, back-off the transmission
- ALHOA
  - If a node has a packet, it draws a random variable and transmits according to the outcome

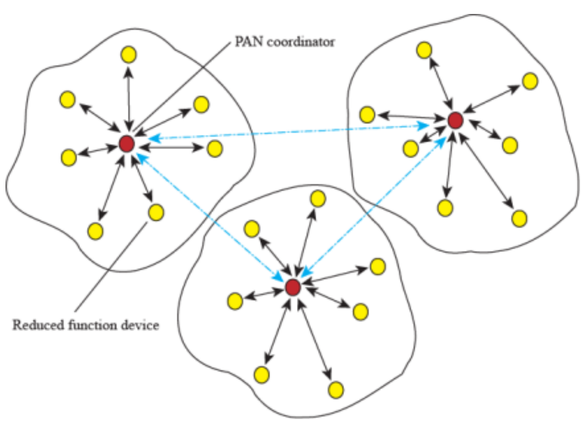
Schedule based MAC (TDMA, FDMA)

Contention based MAC (CSMA, ALHOA)

TDMA

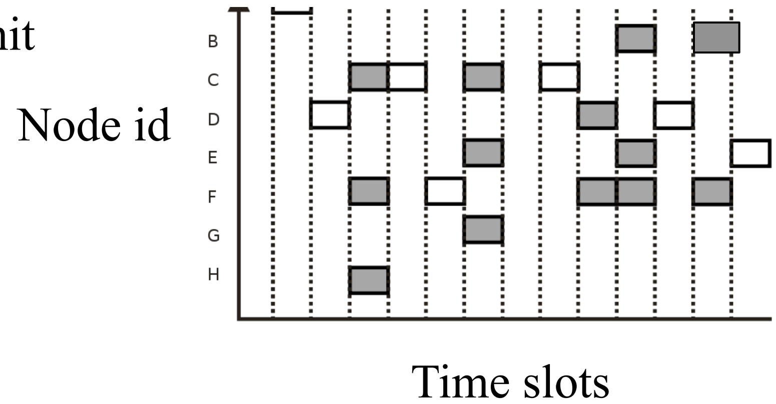
- A central node decides the TDMA schedules
  - simple and no packet collisions
  - burdens the central station
  - not feasible for large networks

- TDMA is useful when network is divided into smaller clusters
  - In each cluster, MAC can be controlled at local head



Slotted ALHOA

n number of nodes attempting to transmit



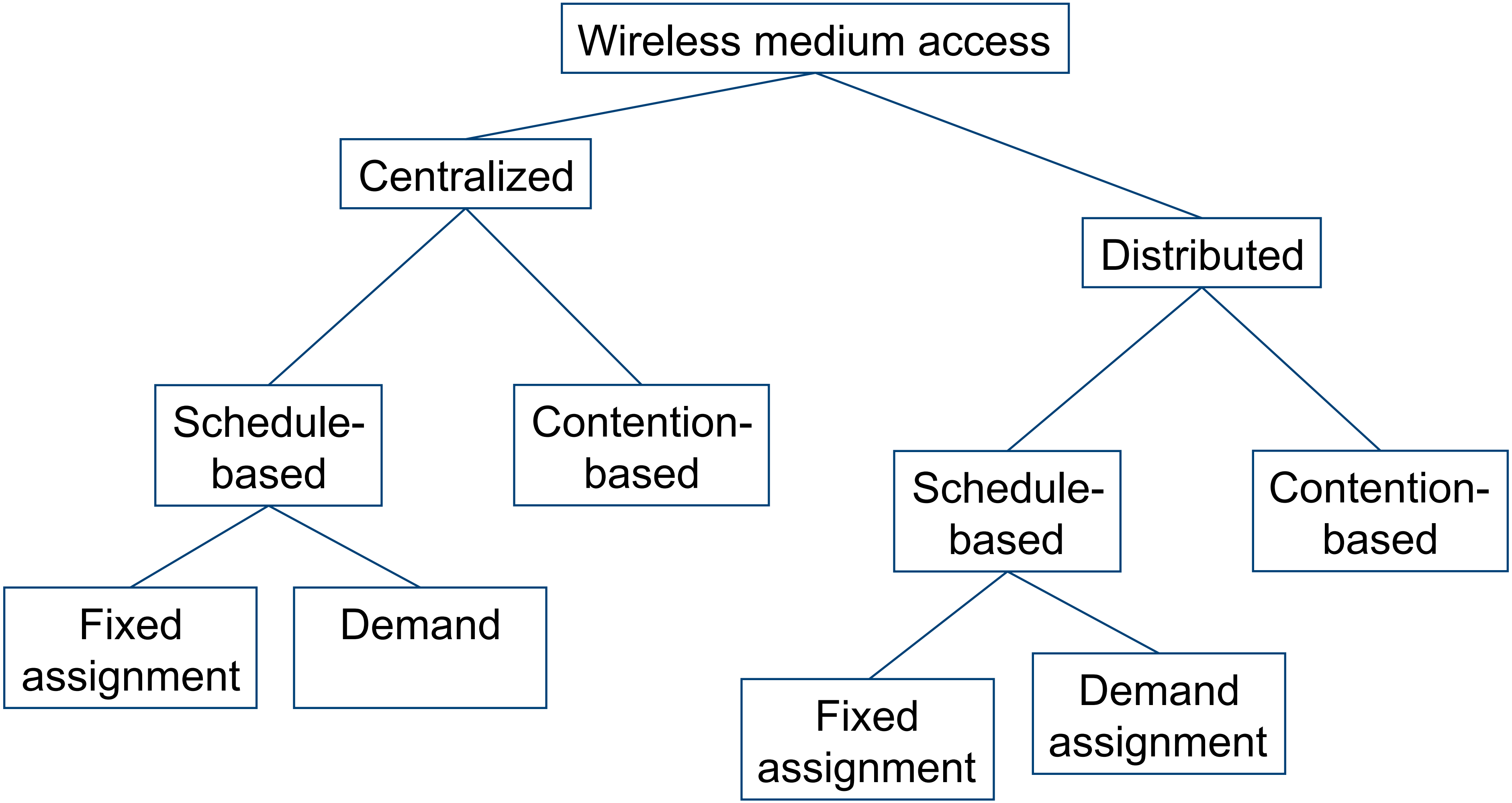
- The slotted ALHOA works on top of TDMA
- Nodes are synchronized
- p probability that a node can transmit a packet
- Probability of successful packet transmission $p(1-p)^{n-1}$
- Probability that a slot is taken $n \cdot p(1-p)^{n-1}$

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

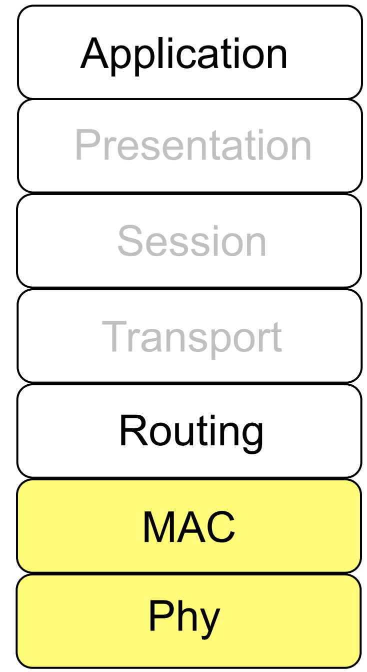
IEEE 802.15.4 protocol architecture

- 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

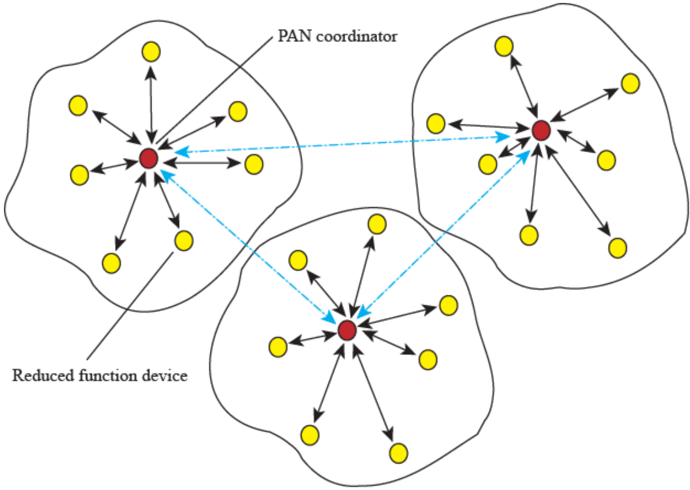
The IEEE 802.15.4 protocol



- 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

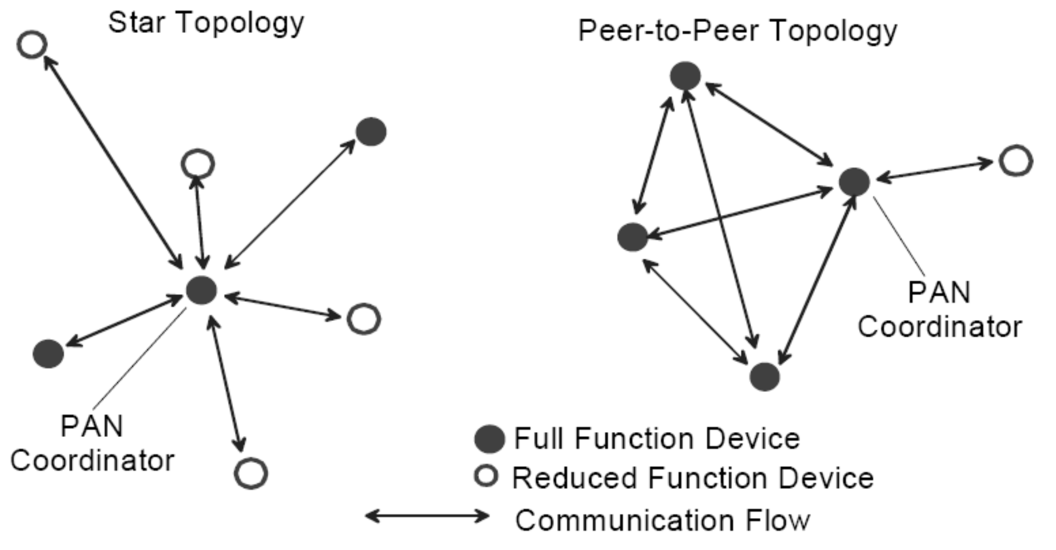
IEEE 802.15.4 networks



- 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

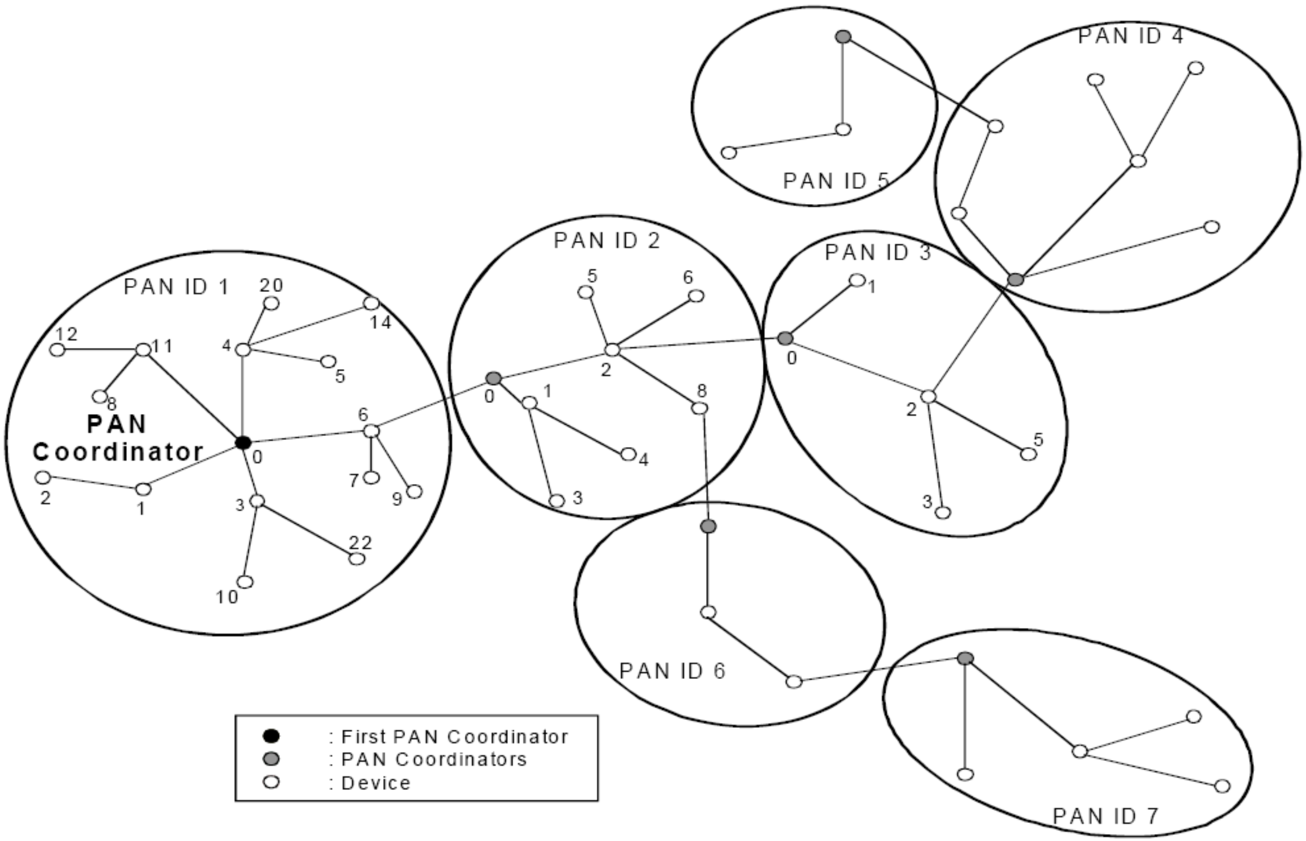
- An FFD can talk to RFDs or FFDs
- RFD can only talk to an FFD

IEEE 802.15.4 network topologies



- 3 types of topologies
  - star topology
  - peer-to-peer topology
  - cluster tree

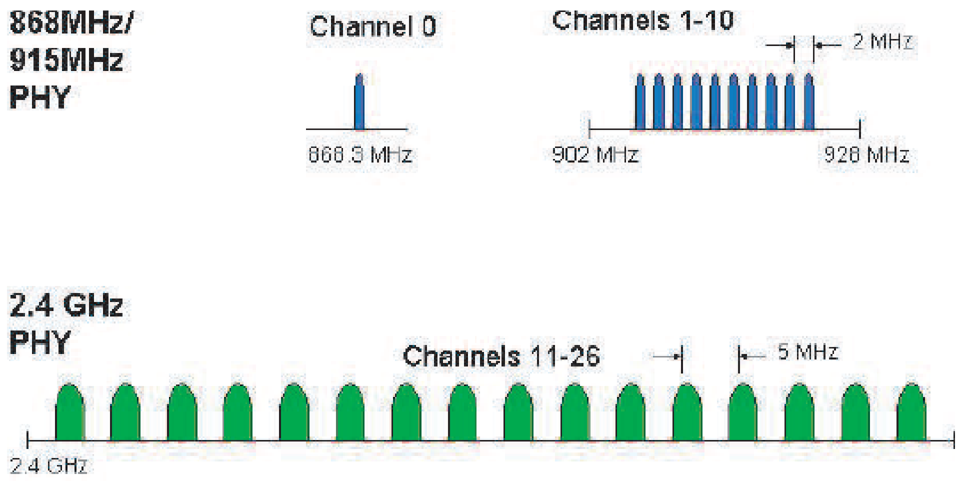
Cluster-tree topology



IEEE 802.15.4 physical layer

- Frequency bands:
  - 2.4 - 2.4835GHz 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	16-ary Orthogonal
	902–928	1000	O-QPSK	250	62.5	16-ary Orthogonal
2450	2400–2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

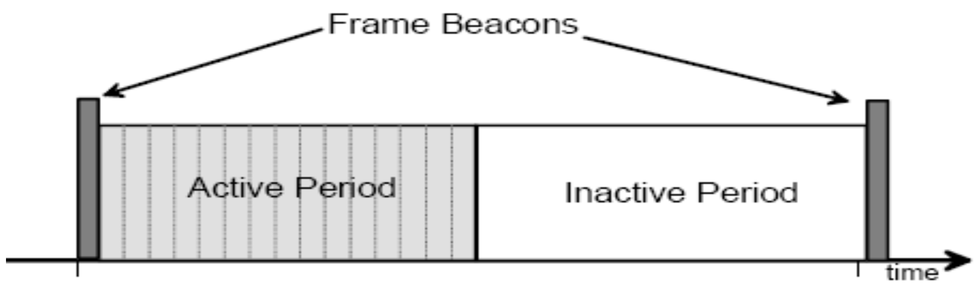
Physical layer data unit

		Octets		
		1		**variable**
Preamble	SFD	Frame length (7 bits)	Reserved (1 bit)	PSDU
SHR		PHR		PHY payload

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

PHR: PHY header
PHY payload < 128 byte

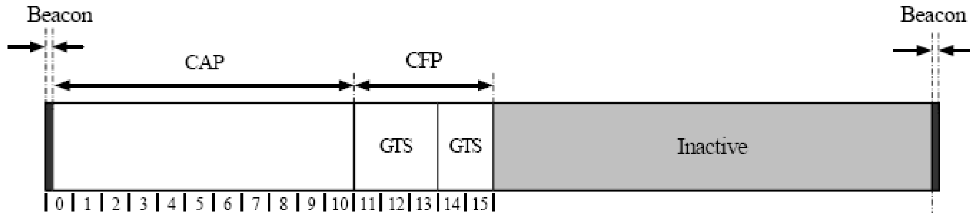
IEEE 802.15.4 MAC

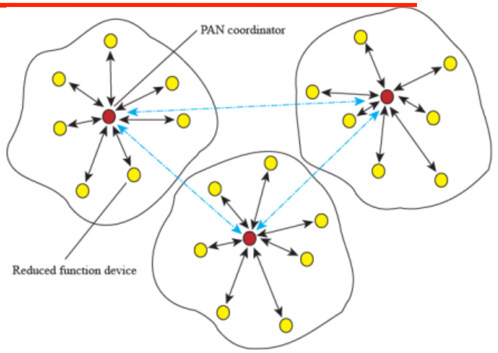


- The MAC provides two services:
  - data service
  - management service

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

Superframes



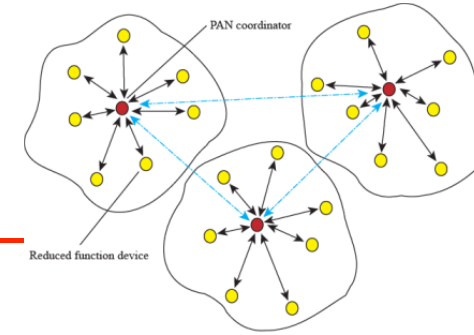


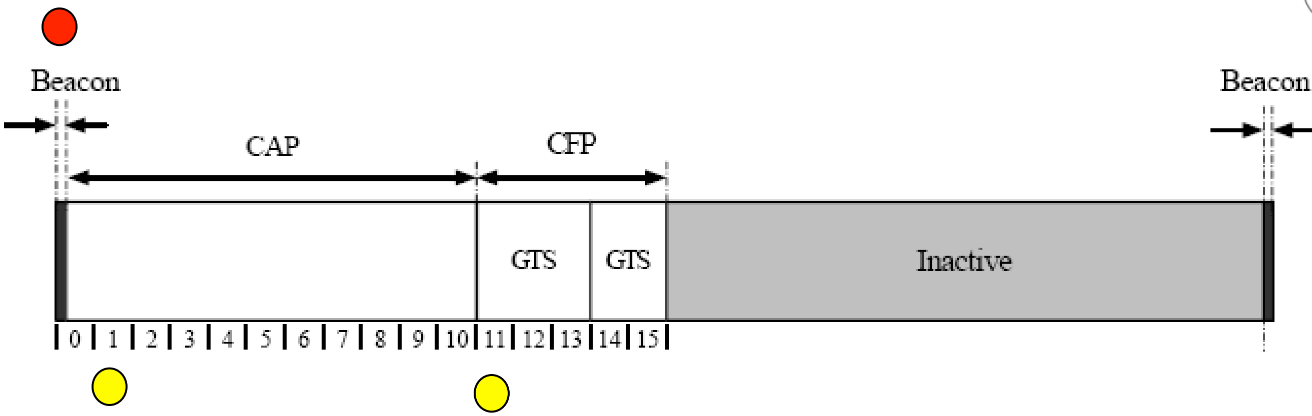
- Superframe structure:
  - format defined by the PAN coordinator
  - bounded by network beacons
  - divided into 16 equally sized slots

- 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





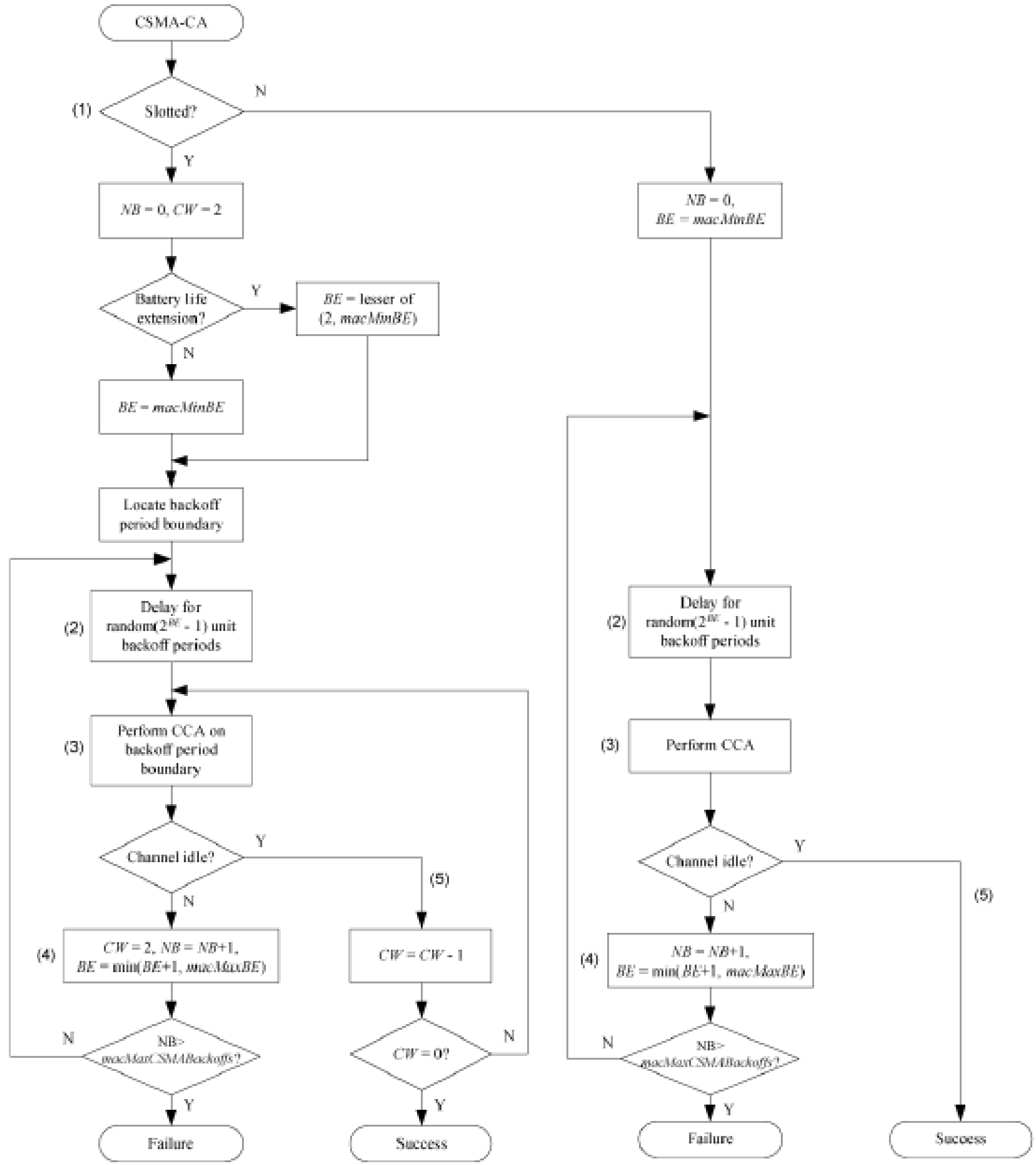
- A Carrier Sense Multiple Access/ Collision Avoidance (CSMA/CA) algorithm is implemented at the MAC layer
- If a superframe structure is used in the PAN, then slotted CSMA-CA is used in the CAP period
- If beacons are not used in the PAN or a beacon cannot be located in a beacon-enabled network, unslotted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

CSMA/CA

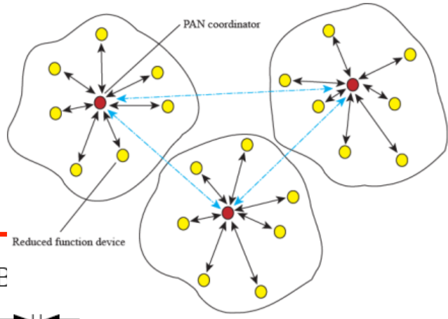
- Each device has 3 variables: NB, CW and BE.
- NB: number of times the CSMA/CA algorithm was required to backoff while attempting the current transmission.
  - It is initialized to 0 before every new transmission.
- BE: backoff exponent
  - how many backoff periods a device shall wait before attempting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

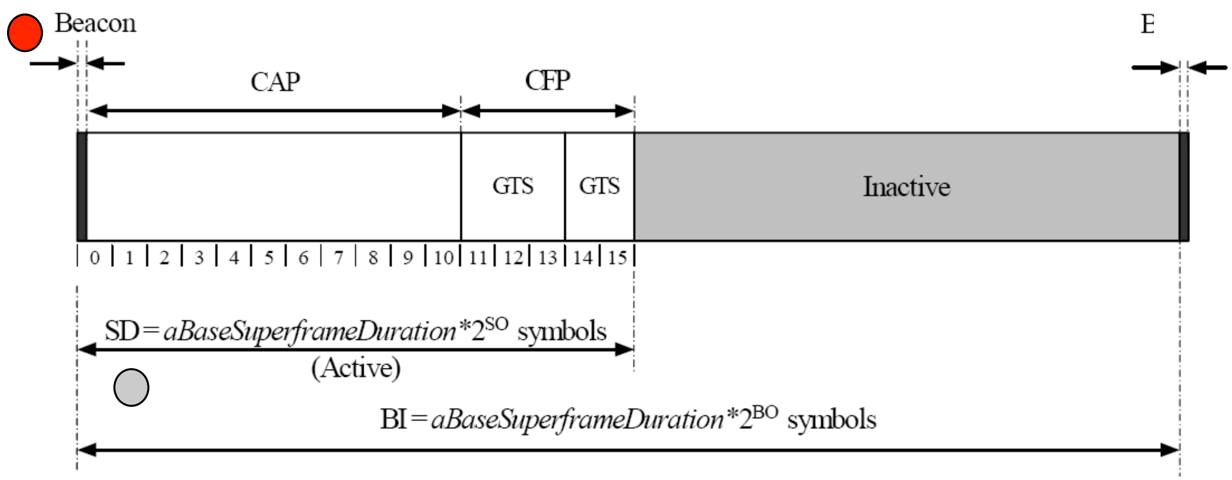
CSMA/CA

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



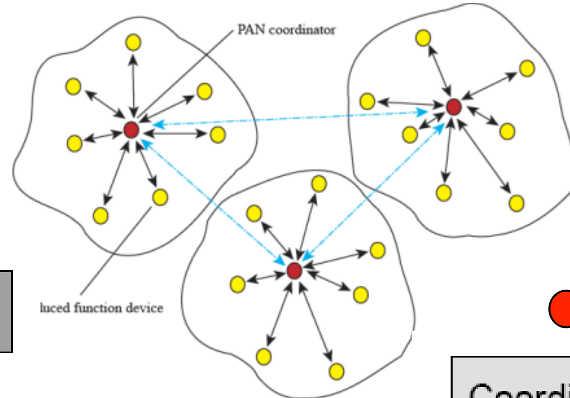


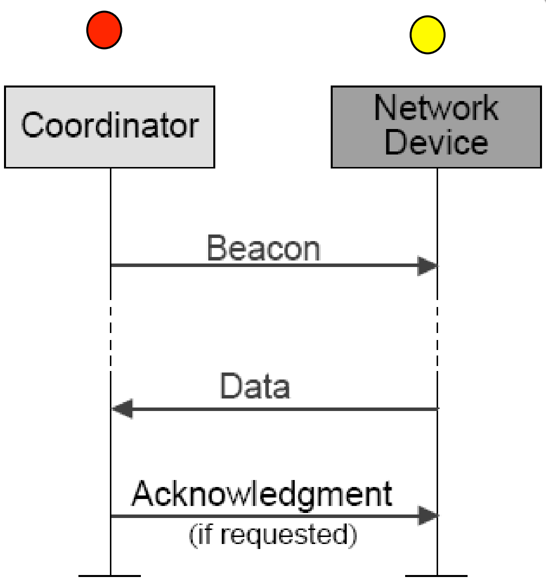
- The GTSs always appears at the end of the active superframe starting at a slot boundary immediately following the CAP.
- The PAN coordinator may allocate up to 7 GTSs.
- A GTS can occupy more than one slot period.
- SO <15. If SO=15, the superframe will not be active anymore after the beacon
- BO 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

GTS

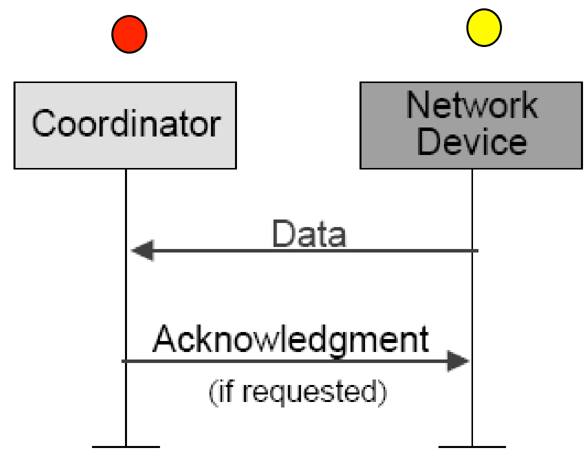
- A GTS allows a device to operate within a portion of the superframe that is dedicated exclusively to it
- A device attempts to allocate and use a GTS only if it is tracking the beacons
- GTS allocation:
  - undertaken by the PAN coordinator only
  - a GTS is used only for communications between the 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



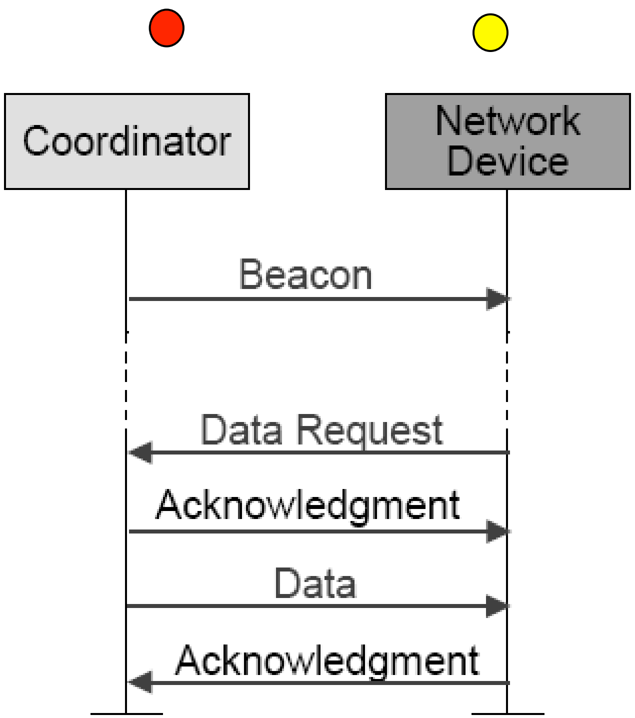


Communication to a coordinator in a beacon-enabled network

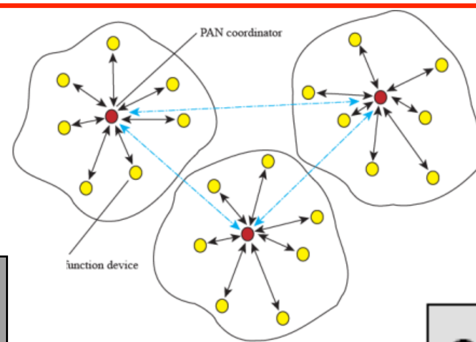


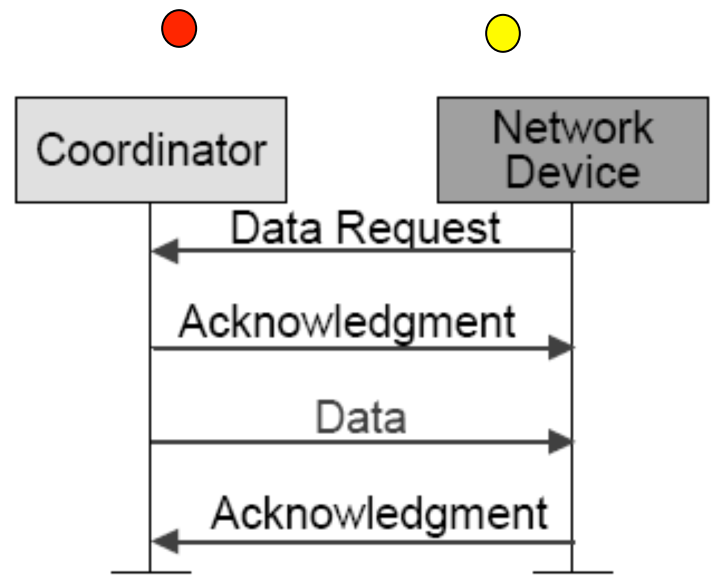
Communication to a coordinator in non-beacon-enabled network

Downlink MAC: Beacon and non-beacon-enabled



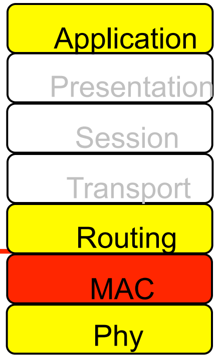
From a coordinator
in a beacon-enabled PAN

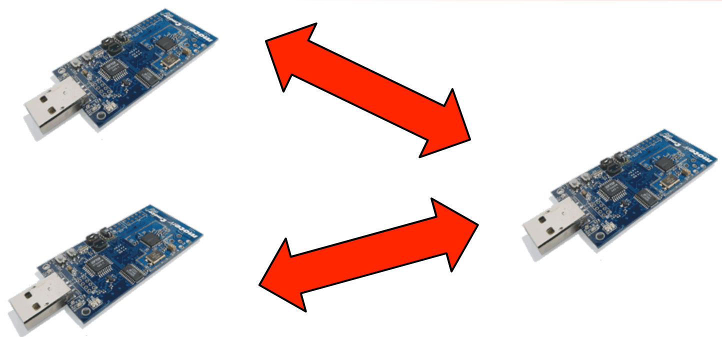




From a coordinator
in a nonbeacon-enabled PAN

Conclusions





- We have seen a MAC classification,
  - ➢ TDMA, ALHOA, 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?