無線網路概論
Intro. to Wireless Internet

Lecture 06 – ZigBee / IEEE 802.15.4

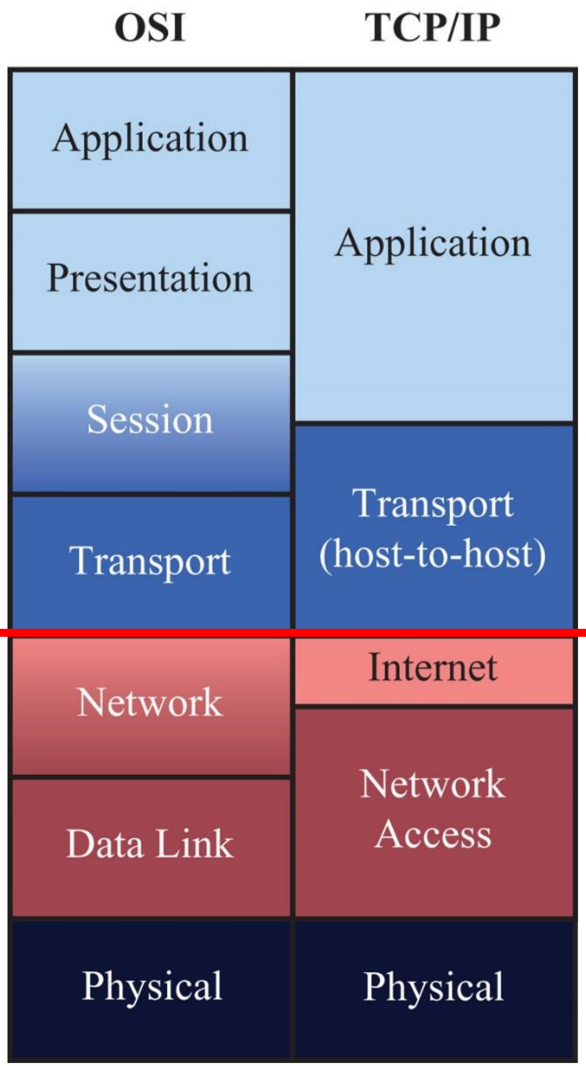
Lecturer: 陳彥安 Chen, Yan-Ann

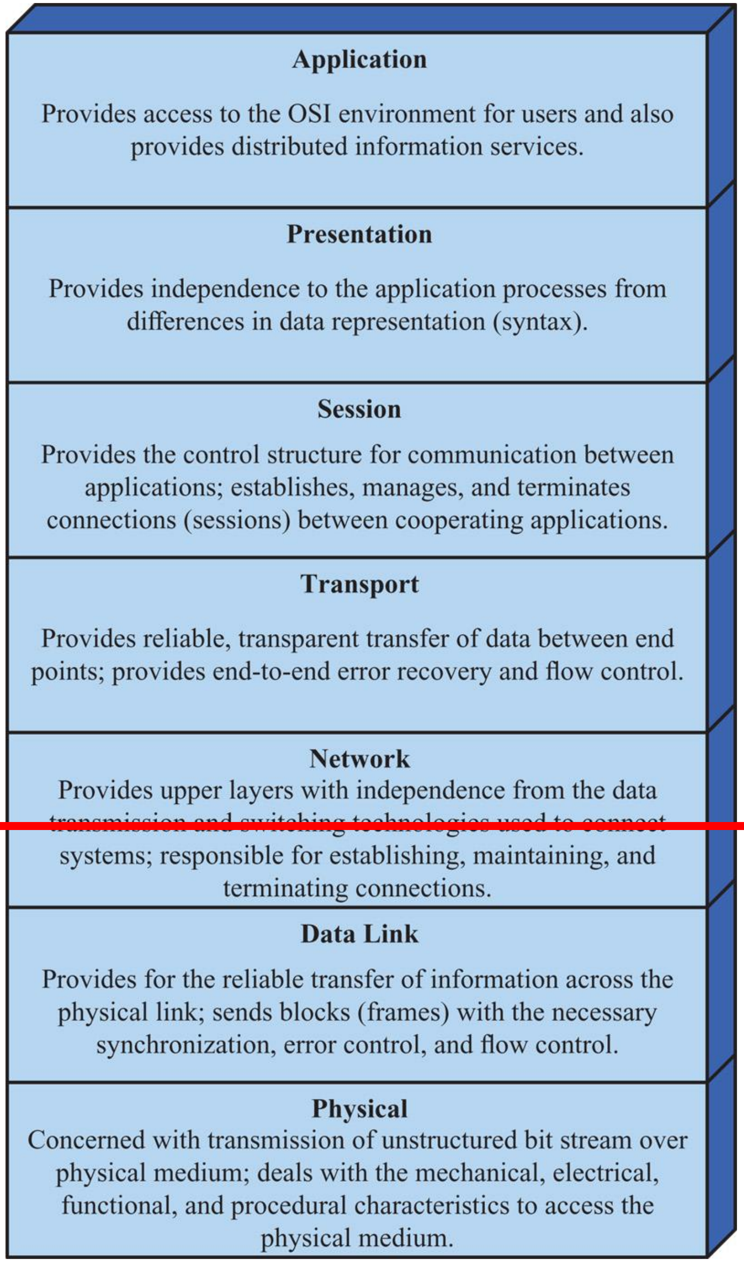
YZU CSE

Lecture Material

- 無線網路 - 通訊協定、感測網路、射頻技術與應用服務, 2011.
  - Ch. 5 - ZigBee
- Wireless Sensor Networks and RFID Technologies
  - NCTU Open Course
  - http://ocw.nctu.edu.tw/course_detail-v.php?bgid=9&gid=0&nid=250
- Wireless Internet
  - Prof. You-Chiun Wang
  - National Sun Yat-sen University

Network System





WPAN

- https://ieeexplore.ieee.org/browse/standards/get-program/page/series?id=68

IEEE 802.15: Wireless PANs

802.15.3-2016

802.15.3-2016 - IEEE Standard for High Data Rate Wireless Multi-Media Networks

802.15.4-2020

802.15.4-2020 - IEEE Standard for Low-Rate Wireless Networks

802.15.5-2009

802.15.5-2009 - IEEE Recommended Practice for Information technology-- Telecommunications and information exchange between systems-- Local and metropolitan area networks-- Specific requirements Part 15.5: Mesh Topology Capability in Wireless Personal Area Networks (WPANs)

802.15.6-2012

802.15.6-2012 - IEEE Standard for Local and metropolitan area networks - Part 15.6: Wireless Body Area Networks

802.15.7-2018

802.15.7-2018 - IEEE Standard for Local and metropolitan area networks--Part 15.7: Short-Range Optical Wireless Communications

802.15.8-2017

802.15.8-2017 - IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Peer Aware Communications (PAC)

802.15.10-2017

802.15.10-2017 - IEEE Recommended Practice for Routing Packets in IEEE 802.15.4 Dynamically Changing Wireless Networks

802.15.22.3-2020

802.15.22.3-2020 - IEEE Standard for Spectrum Characterization and Occupancy Sensing

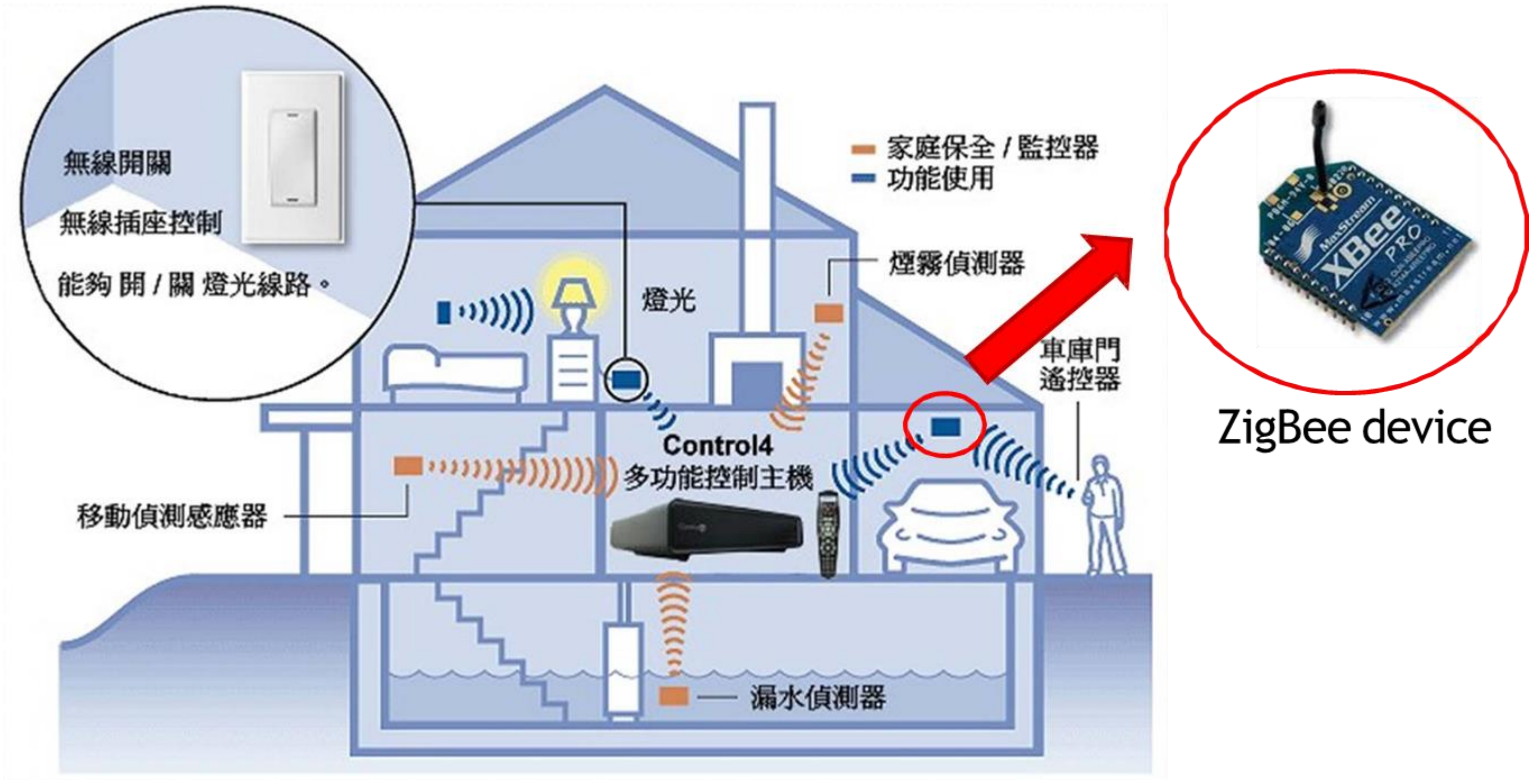
Outline

- ZigBee vs. IEEE 802.15.4
- IEEE 802.15.4: Physical layer
- IEEE 802.15.4: MAC layer
- ZigBee: Network layer

What is ZigBee?

- ZigBee is developed for control and sensor networks.
  - It provides simple wireless connectivity, relaxed throughput, very low power, short distance, and inexpensive hardware.
  - ZigBee is based on the IEEE 802.15.4 standard and created by the ZigBee alliance.
- ZigBee potential applications:
  - Industrial
  - Agricultural
  - Vehicular
  - Residential

Smart-home Application



米家智慧插座ZigBee 白色

NT$495

米家門窗感應器 白色

NT$245

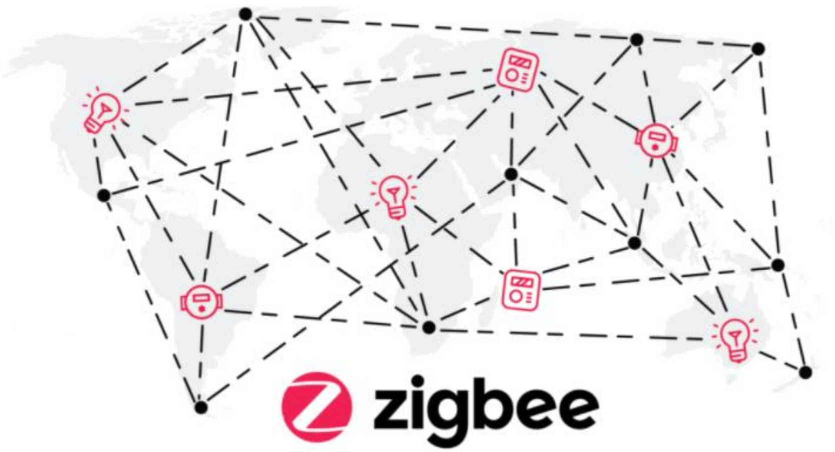
2年
無需更換電池
低功耗

免安裝
隨貼即用

15ms
快速響應

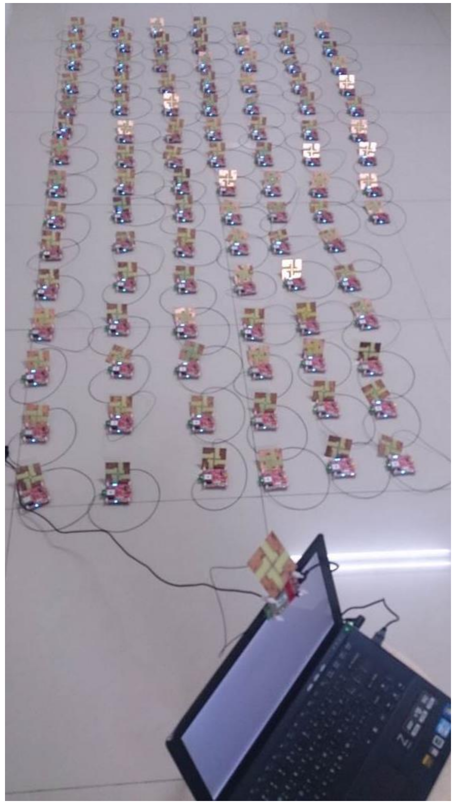
Connectivity Standards Alliance

- Connectivity Standards Alliance (formerly the Zigbee Alliance)
- ZigBee alliance is an international organization whose mission is to define reliable, cost-effective, low-power, wirelessly networked, monitoring and control products based on an open global standard.
  - https://csa-iot.org/all-solutions/zigbee/
- This alliance also provides interoperability, certification testing, and branding.

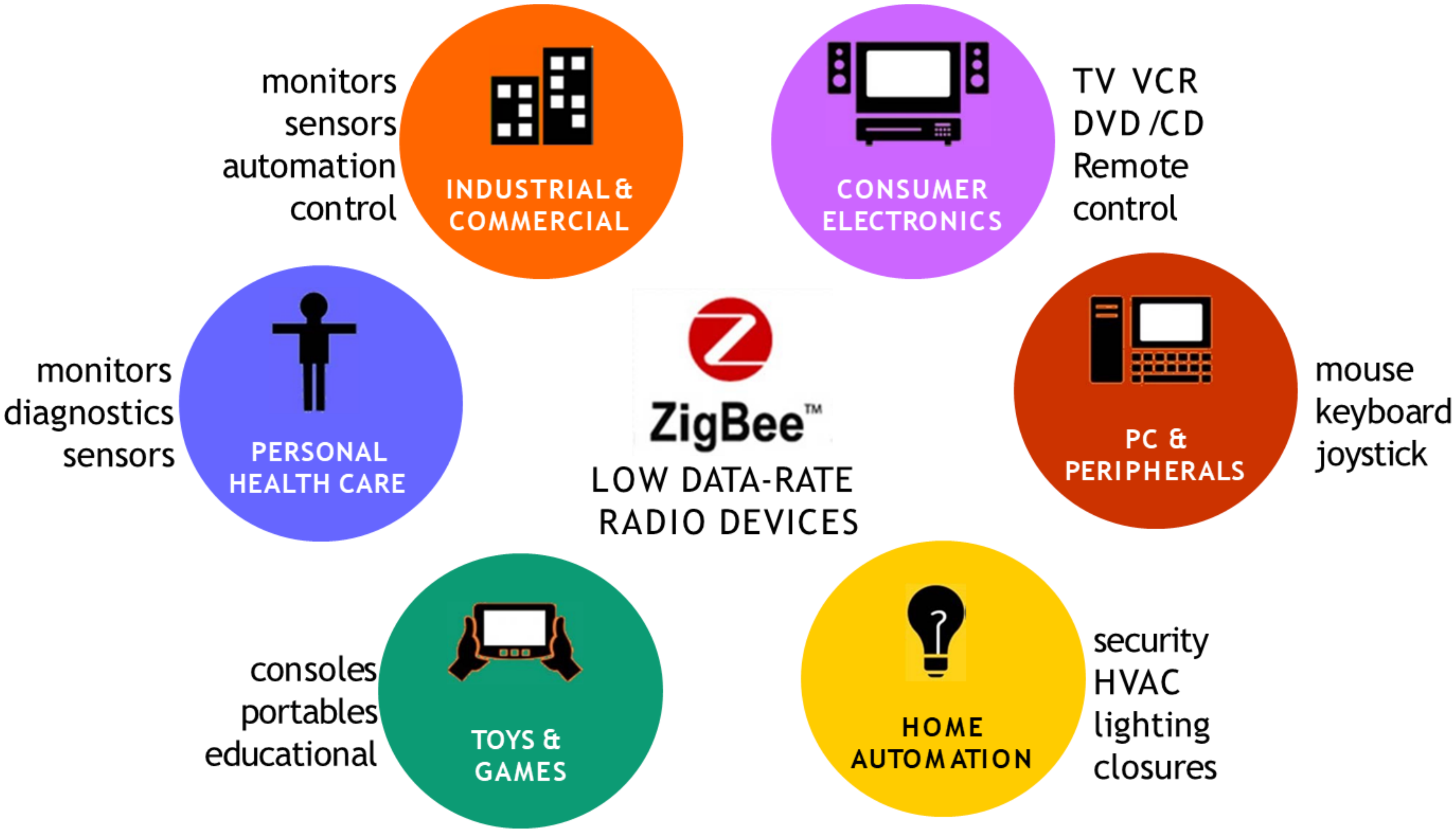


Market Targets of ZigBee

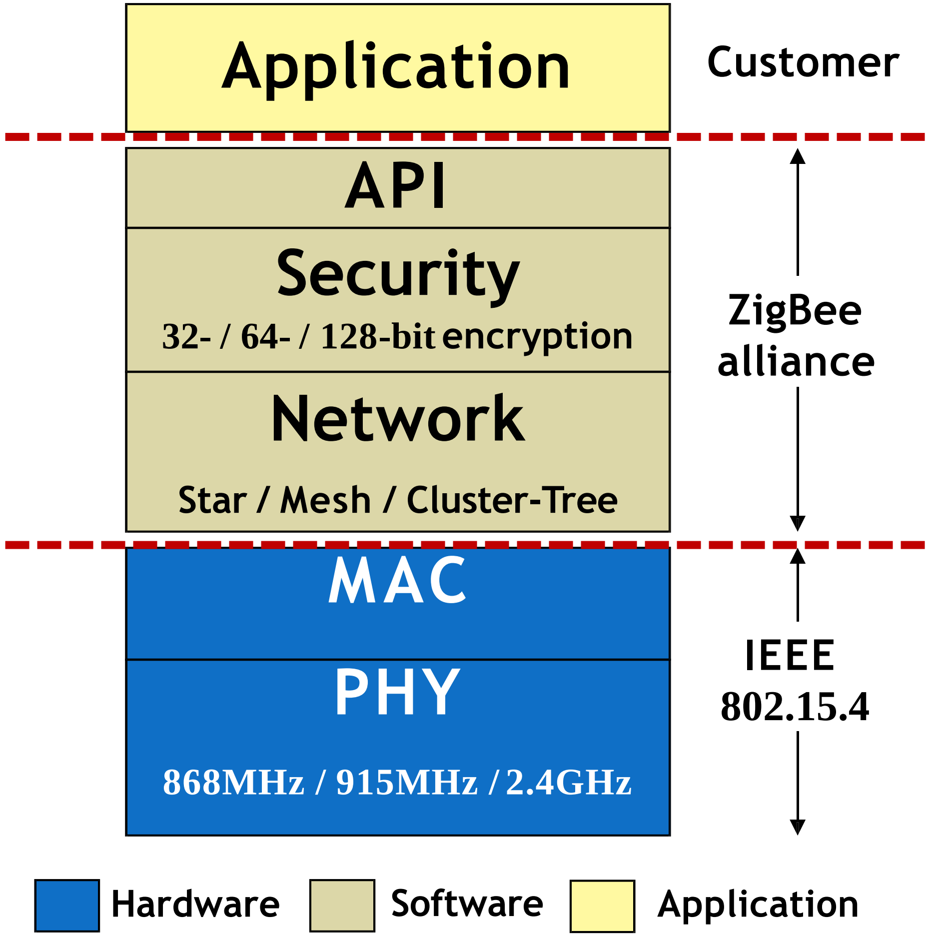
- Low power consumption
- Low cost
- Low offered message throughput
- Low to no QoS guarantees
- Support large network orders (up to 65,000 nodes)
- Flexible protocol design suitable for many applications



ZigBee Applications



ZigBee Protocol Stack



ZigBee Alliance

- Define **software** behaviors.
- Network, security & application layers

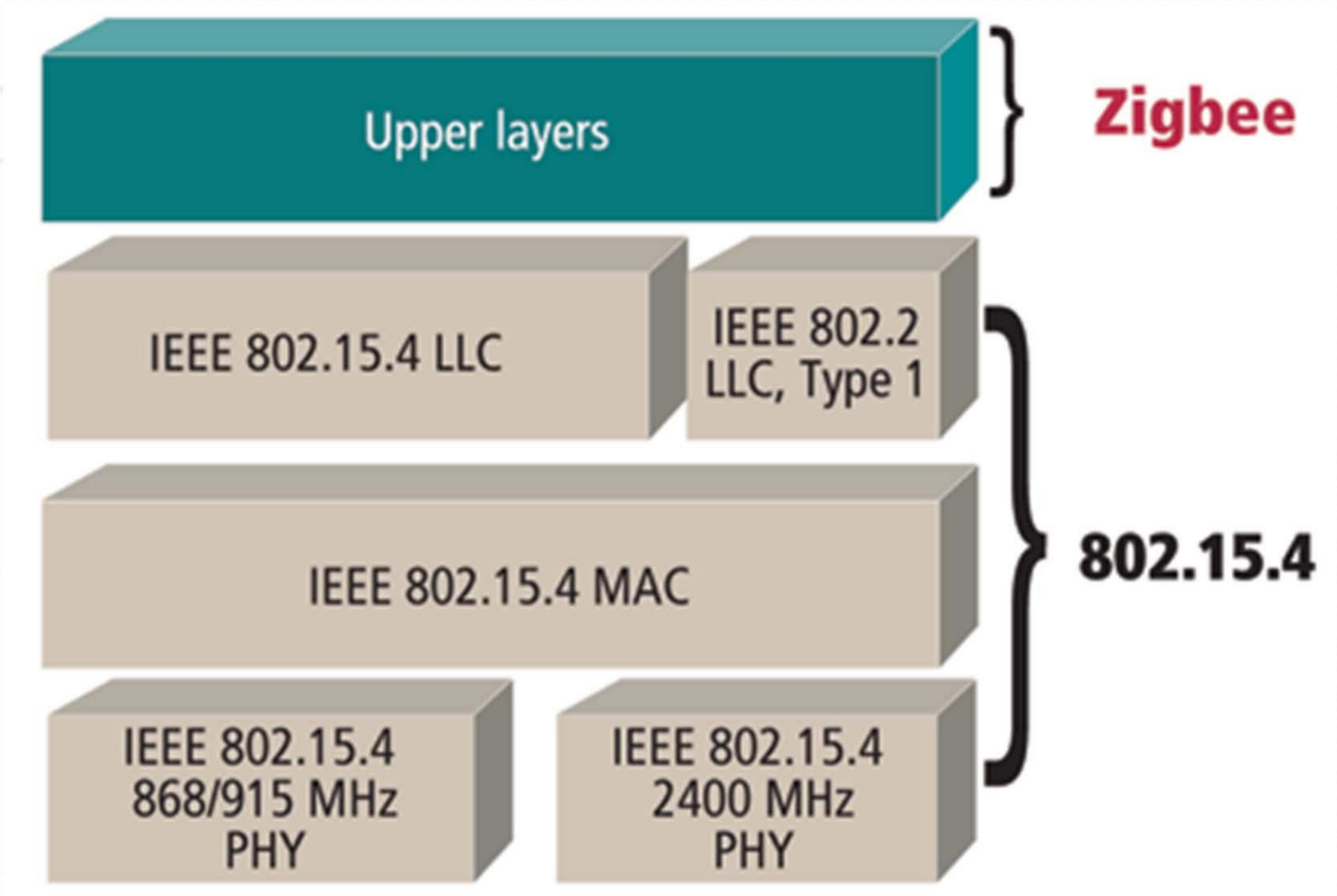
IEEE 802.15.4

- Define **hardware** behaviors.
- Physical & MAC layers

IEEE 802.15.4 Overview

- IEEE 802.15.4 is a standard developed for lightweight wireless networks.
  - Channel access is realized by CSMA/CA and optional time slotting.
  - Message acknowledgement mechanism
  - Optional beacon structure
- Goals of IEEE 802.15.4:
  - Longer battery life
  - Selectable latency for controllers, sensors, remote monitoring, and portable electronics

IEEE 802.15.4 Architecture



Features of IEEE 802.15.4 (1/2)

- IEEE 802.15.4 supports very low data rates, which are suitable for low-throughput but low-latency devices.
  - Three supported rates: 20 kbps, 40 kpbs, and 250 kbps
- Network operates in the star or peer-to-peer fashions.
- IEEE 802.15.4 adopts CSMA/CA mechanism for channel access.
- IEEE 802.15.4 also adopts fully-handshake protocol for transfer reliability.
  - ACK mechanism

Features of IEEE 802.15.4 (2/2)

- IEEE 802.15.4 supports dynamic device addressing.
- IEEE 802.15.4 supports low power consumption, and thus allows extremely low duty-cycle (< 0.1%).
- Operation channels:
  - 16 channels in the 2.4GHz ISM band
  - 10 channels in the 915MHz ISM band
  - 1 channel in the European 868MHz band

Devices Defined in IEEE 802.15.4

- IEEE 802.15.4 defines two types of devices:
  - FFD: Full function device
  - RFD: Reduced function device
- An FFD can operate in three modes by serving as:
  - Device
  - Coordinator
  - PAN coordinator
- An RFD can only serve as:
  - Device

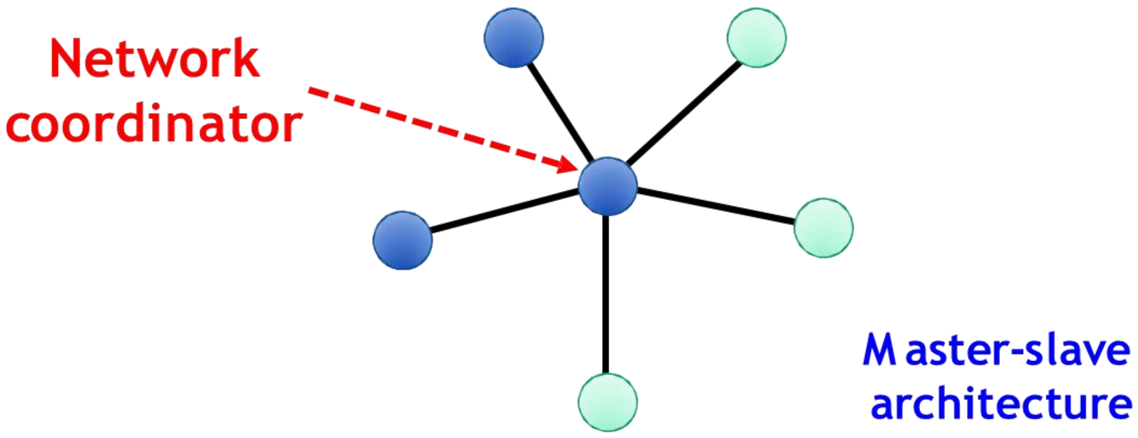
FFD: Full Function Device

- FFD can operate in both star and peer-to-peer network topologies.
- FFD can serve as a network coordinator and thus is able to talk to any other device.
  - Example: Smart phone or controller

RFD: Reduced Function Device

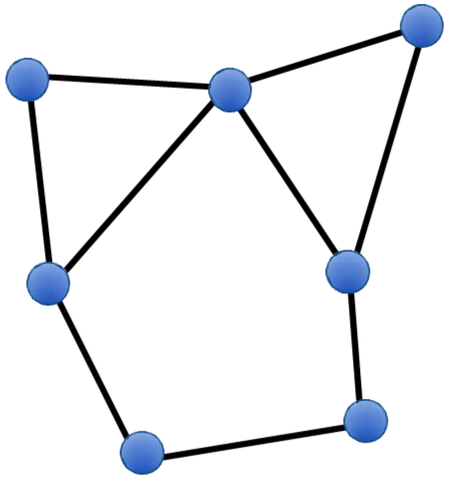
- RFD cannot become a network coordinator and therefore is limited to the star network topology.
- RFD usually has very simple implementation and can talk only to a network coordinator.
  - Example: Switch

Network Topology

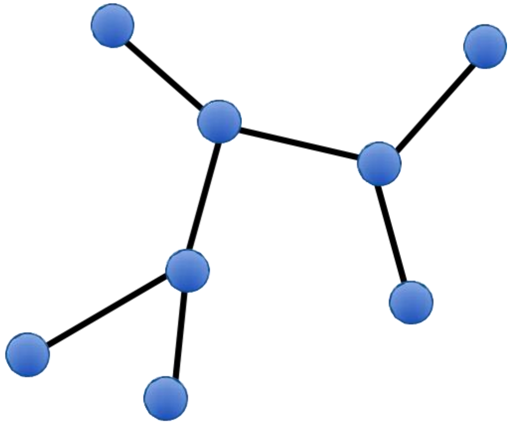


- Full function device (FFD)
- Reduced function device (RFD)
- Communication link

Star



Point to point

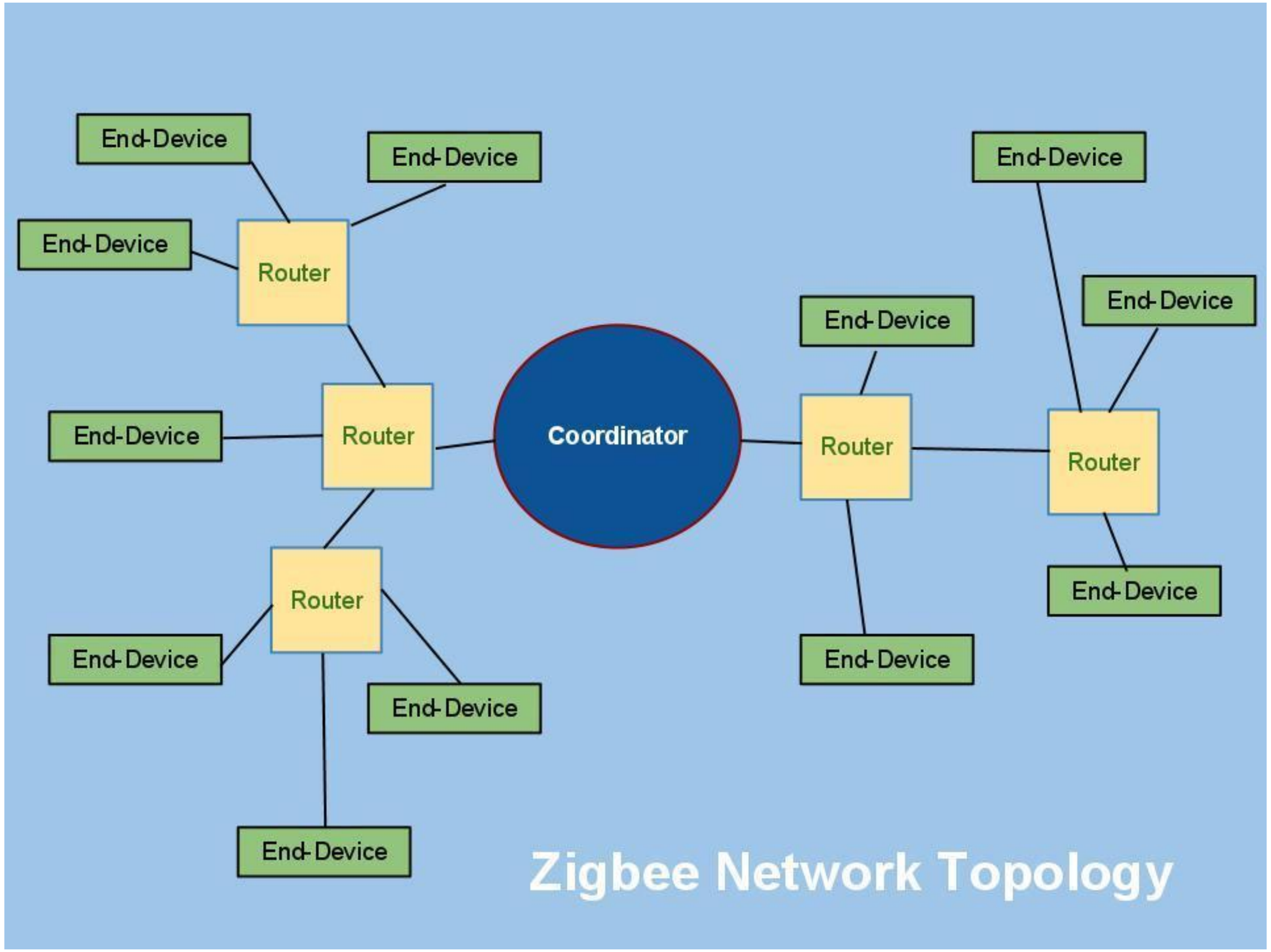


Tree

- Full function device (FFD)
- Communication link

Peer-to-Peer

Network Topology



Ref: https://seeeddoc.github.io/Zigbee_Networking_with_XBee_Series_2_and_Seeed-s_Products/

IEEE 802.15.4 PAN

- Two or more IEEE 802.15.4 devices communicating on the same physical channel constitute a PAN.
  - PAN: Personal area network
  - A PAN should include at least one FFD (to serve as the PAN coordinator).
- Each independent PAN has a unique PAN identifier.

Device Addressing

- In IEEE 802.15.4, each device operating on a PAN has a unique 64-bit extended address.
  - This address can be used for direct communication in the PAN.
- A device also has a 16-bit short address, which is allocated by the PAN coordinator when this device associates with its coordinator.

ZigBee vs. IEEE 802.15.4

- How is ZigBee related to IEEE 802.15.4?
  - ZigBee takes full advantage of a powerful physical radio specified by IEEE 802.15.4.
  - ZigBee adds logical network, security, and application software.
  - ZigBee continues to work closely with the IEEE standard to ensure an integrated and complete solution for the market.

IEEE 802.15.4

Outline

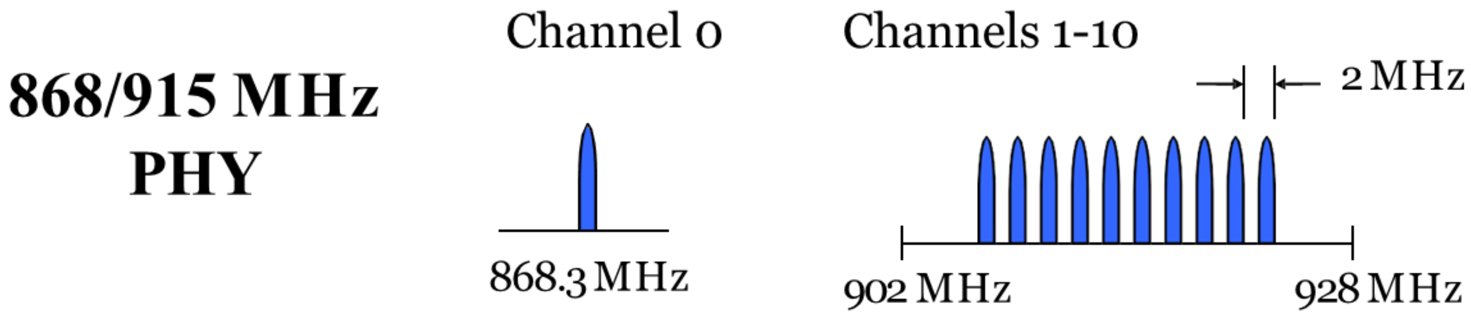
- ZigBee vs. IEEE 802.15.4
- IEEE 802.15.4: Physical layer
- IEEE 802.15.4: MAC layer
- ZigBee: Network layer

PHY Functionalities

- IEEE 802.15.4 physical layer provides the following functionalities:
  - Activation and deactivation of the radio transceiver
  - Energy detection within the current channel
  - Link quality indication for received packets
  - Clear channel assessment (i.e., carrier sensing) for CSMA/CA
  - Channel frequency selection
  - Data transmission and reception

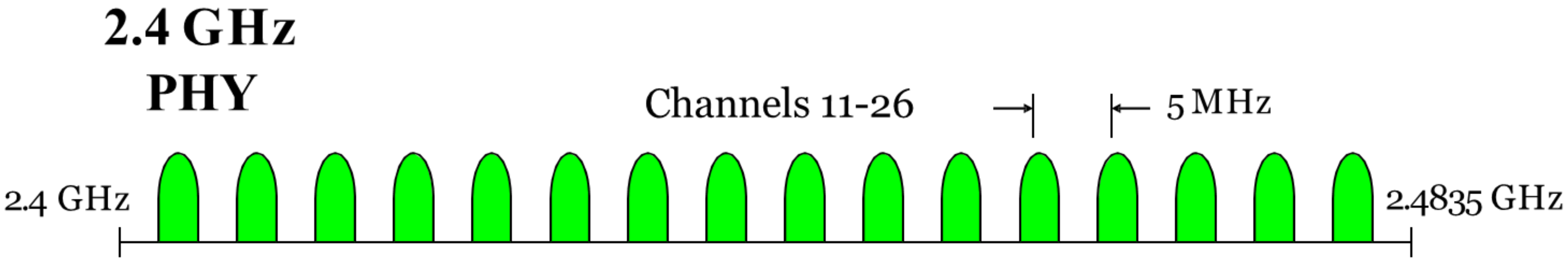
Frequency Bands – 868/915MHz

- IEEE 802.15.4 defines 11 channels in 868/915 MHz.
  - European band: Channel 0 operated in 868 MHz
    - Support data rate of 20 Kb/s.
  - ISM band: Channels 1~10 operated in 902~928 MHz
    - Support data rate of 40 Kb/s.
    - Each channel is separated by 2 MHz.



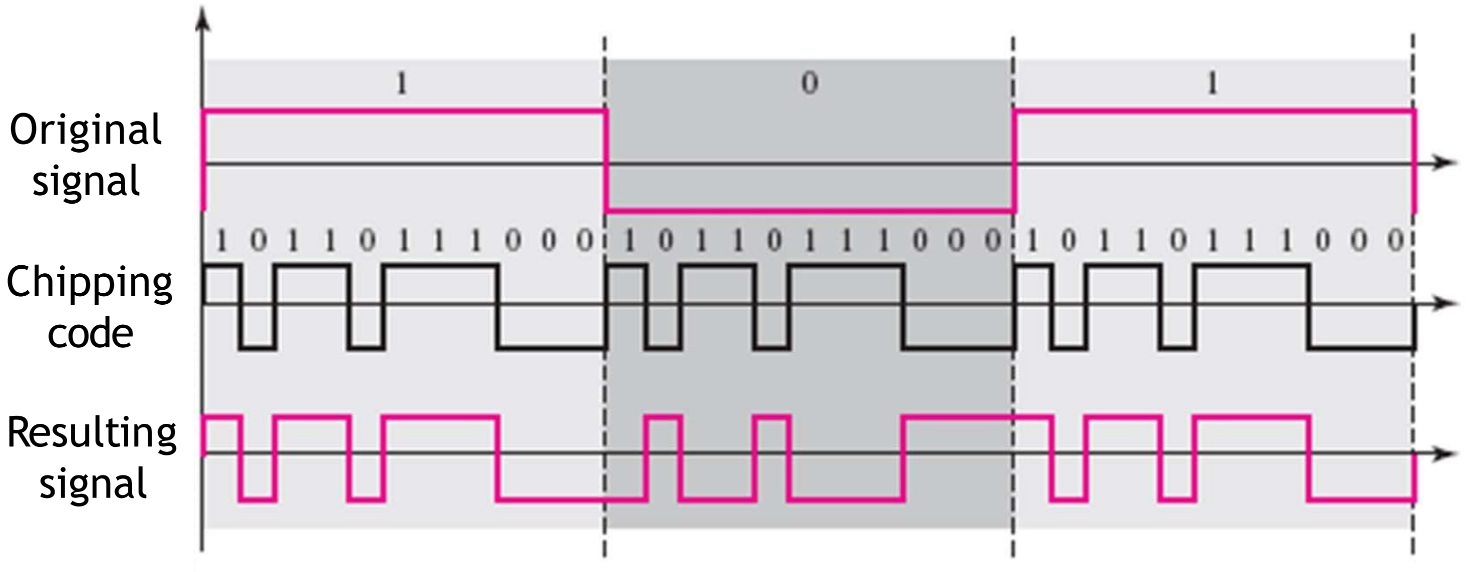
Frequency Bands – 2.4 GHz

- IEEE 802.15.4 defines 16 channels in 2.4 GHz.
  - ISM band: Channels 11~26 operated in 2.4~2.4835 GHz
    - Support data rate of 250 Kb/s.
    - Each channel is separated by 5 MHz.



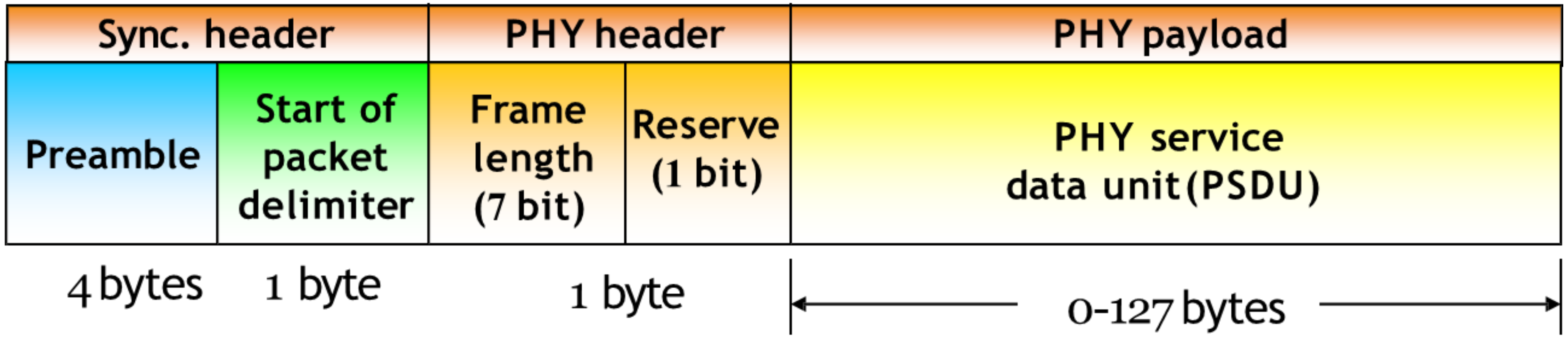
Spreading Spectrum

- IEEE 802.15.4 employs direct sequence spread spectrum (DSSS) for operating in ISM band.
  - Input data stream is transferred to a chip stream that is k times higher by XOR.



PHY Frame Structure

- PHY packet fields:
  - Preamble (4 bytes): For synchronization purpose
  - Start of packet delimiter (1 byte): Formatted as “11100101”
  - PHY header (1 byte): Use 7 bits to indicate the PSDU length.
  - PSDU (0 to 127 bytes): Data field

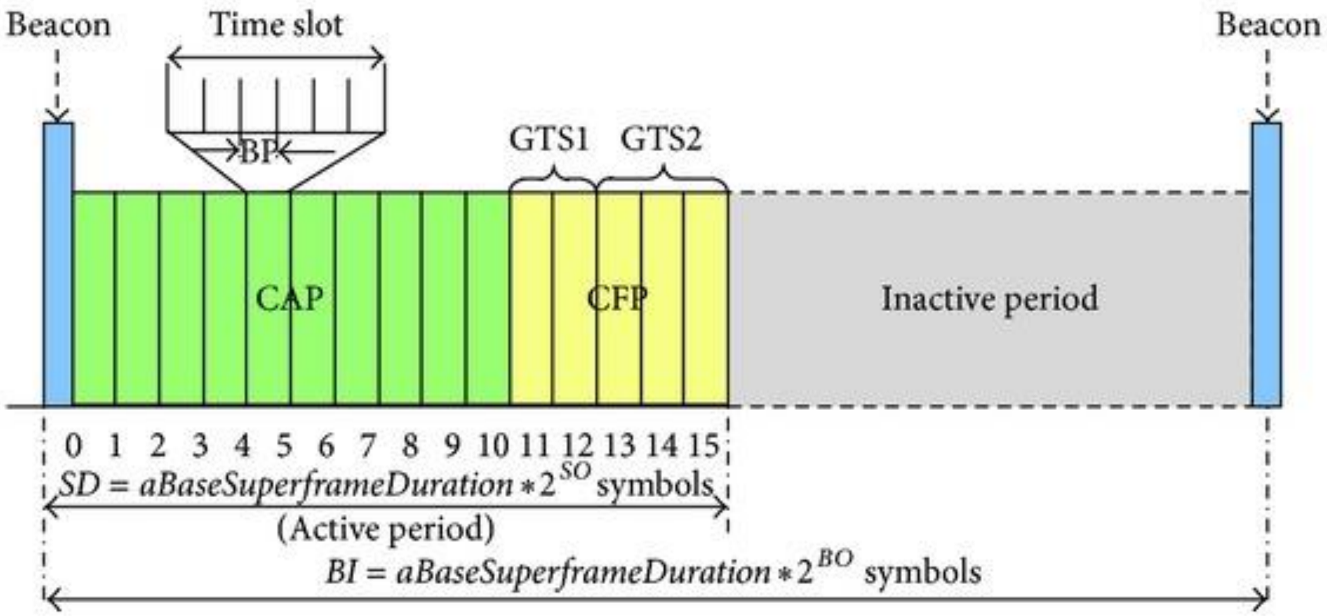


Outline

- ZigBee vs. IEEE 802.15.4
- IEEE 802.15.4: Physical layer
- IEEE 802.15.4: MAC layer
- ZigBee: Network layer

MAC Superframe

- IEEE 802.15.4 MAC superframe is divided into two parts:
  - Inactive part: All devices go to sleep.
  - Active part: Further divided into two parts
    - Contention access period (CAP)
    - Contention free period (CFP)



How to decide superframe length?

- The structure of a superframe is decided by two parameters:
  - Beacon order (BO): Decide the length of a superframe.
  - Superframe order (SO): Decide the length of the active potion in a superframe.
- For a beacon-enabled network, the setting of BO and SO should satisfy the relationship of $0 \leq SO \leq BO \leq 14$.
- For channels 11 to 26 (in 2.4 GHz), the superframe length can range from 15.36 ms to 215.7 seconds (= 3.6 minutes).

Duty Cycle in IEEE 802.15.4 MAC

- Each device becomes active for $\frac{1}{2^{BO-SO}}$ portion of time, and sleep for $1 - \frac{1}{2^{BO-SO}}$ portion of the time.
- Duty cycle:

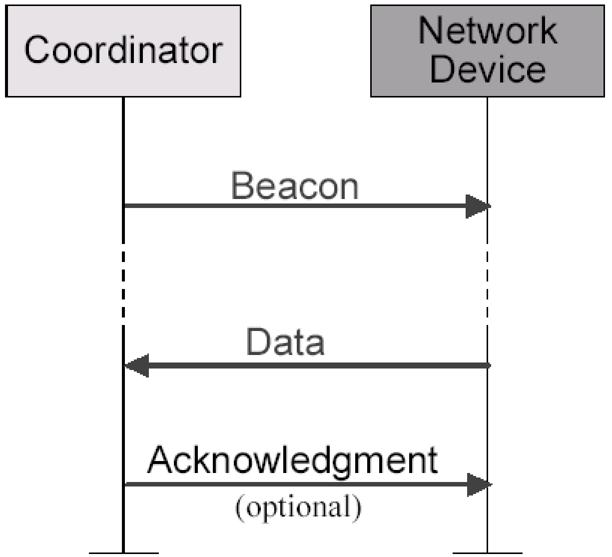
BO-SO	0	1	2	3	4	5	6	7	8	9	≥ 10
Duty cycle (%)	100	50	25	12	6.25	3.125	1.56	0.78	0.39	0.195	< 0.1

MAC Beacon

- In IEEE 802.15.4, the purposes of beacons are:
  - Indicate the start of superframes.
  - Synchronize with other devices.
  - Announce the existence of a PAN.
  - Inform pending data in coordinators.
- In a beacon-enabled network:
  - Devices use the slotted CSMA/CA mechanism to contend for the usage of channels.
  - FFDs which require fixed rates of transmissions can ask for guarantee time slots (GTS) from the coordinator.

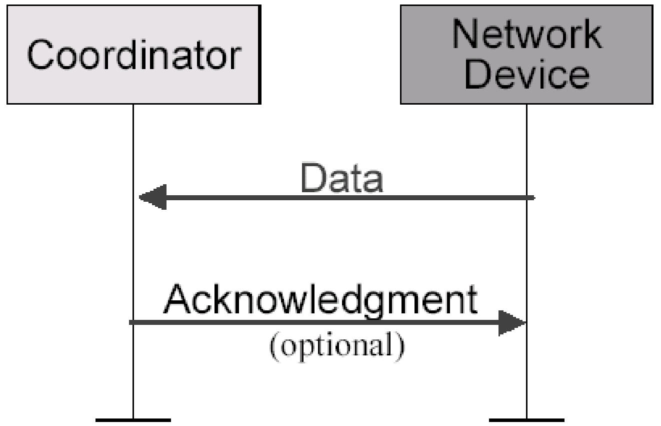
Data Transfer Model: Case 1

- Data transferred from a network device to the coordinator in a beacon-enabled network:
  - Device finds the beacon to synchronize to the superframe structure.
  - Then, it uses slotted CSMA/CA to transmit data.



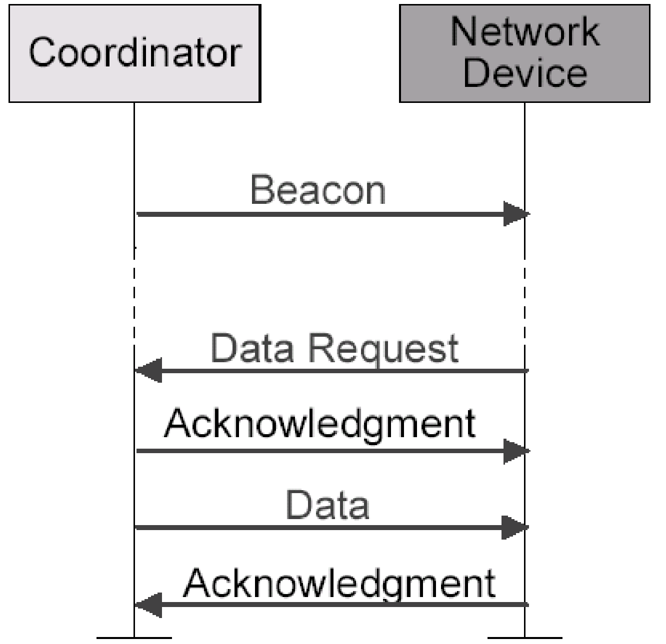
Data Transfer Model: Case 2

- Data transferred from a network device to the coordinator in a non-beacon-enabled network:
  - Device simply transmits data using unslotted CSMA/CA.



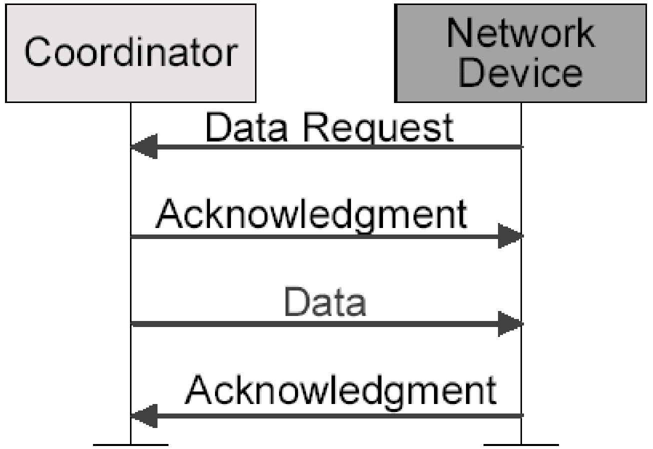
Data Transfer Model: Case 3

- Data transferred from the coordinator to a network device in a beacon-enabled network:
  - Coordinator indicates in the beacon that there are pending data.
  - A device periodically listens to the beacon and transmits a data request using slotted CSMA/CA.
  - Then, ACK, data, and ACK follow…



Data Transfer Model: Case 4

- Data transferred from the coordinator to a network device in a non-beacon-enabled network:
  - Device transmits a data request using unslotted CSMA/CA.
  - Coordinator replies an ACK.
  - Then, the coordinator transmits data using unslotted CSMA/CA.
  - If there is no pending data, a data frame with zero-length payload is transmitted.



Channel Access Mechanism

- IEEE 802.15.4 defines two types of channel access mechanisms:
  - Beacon-enabled networks
    -> Slotted CSMA/CA channel access mechanism
  - Non-beacon-enabled networks
    -> Unslotted CSMA/CA channel access mechanism

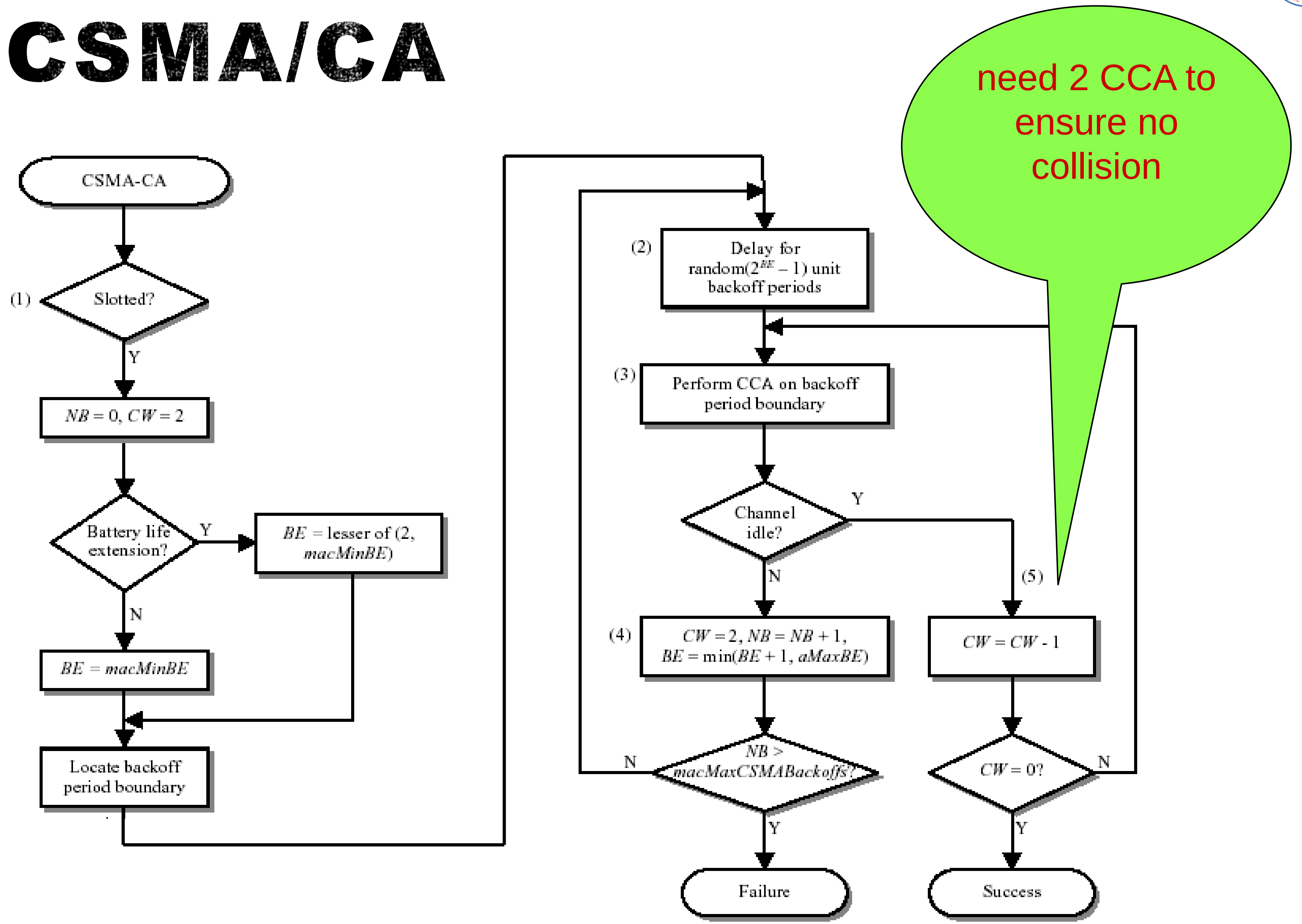
Slotted CSMA/CA: Guideline

- The backoff period boundaries of every device in PAN should be aligned with the superframe’s slot boundaries of the PAN coordinator.
  - In other words, the start of first backoff period of each device is aligned with the start of the beacon transmission.
- MAC layer should ensure that PHY layer commences all of its transmissions on the boundary of a backoff period.

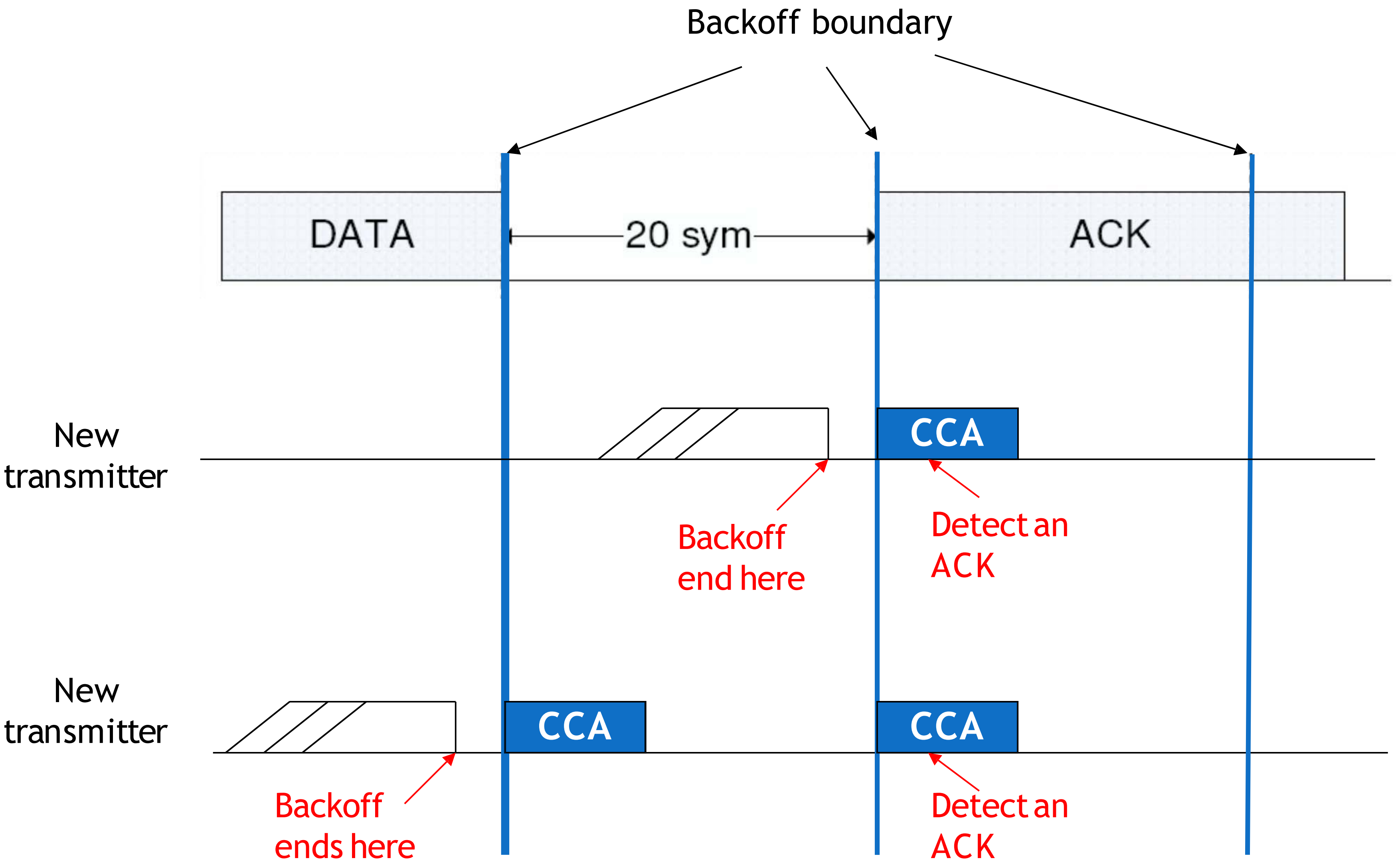
Slotted CSMA/CA: Parameters

- Each device maintains three parameters for each transmission attempt.
  - NB: Number of times that backoff has been taken in this attempt
    - If NB > macMaxCSMABackoff, the attempt fails.
  - BE: Backoff exponent which is determined by NB
  - CW = 2: Length of contention window, which is the number of clear slots that must be seen after each backoff
    - The design is for some PHY parameters, which require two clear channel assessment (CCA) for efficient channel usage.

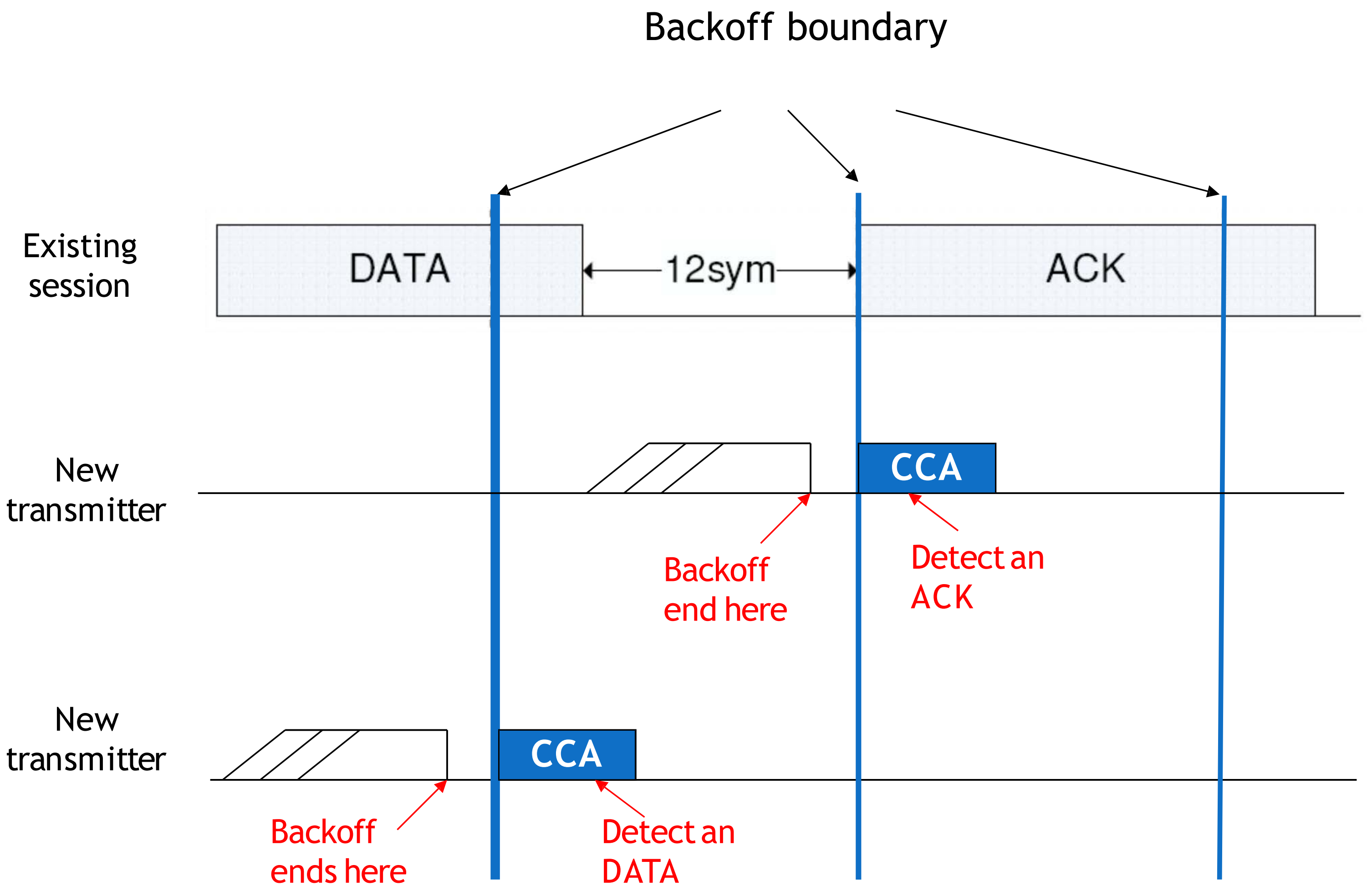
Slotted CSMA/CA



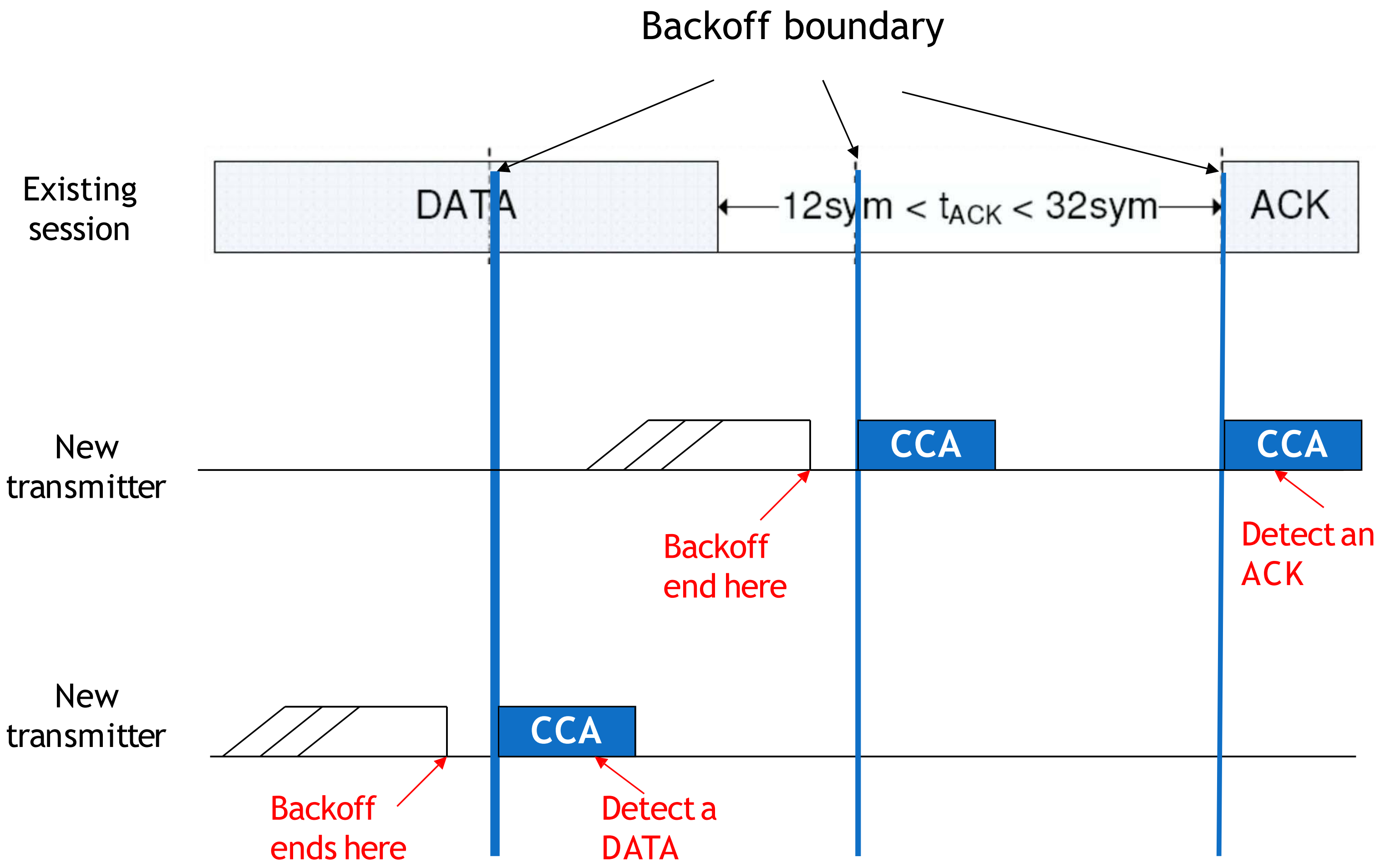
Why 2 CCAs? (Case 1)



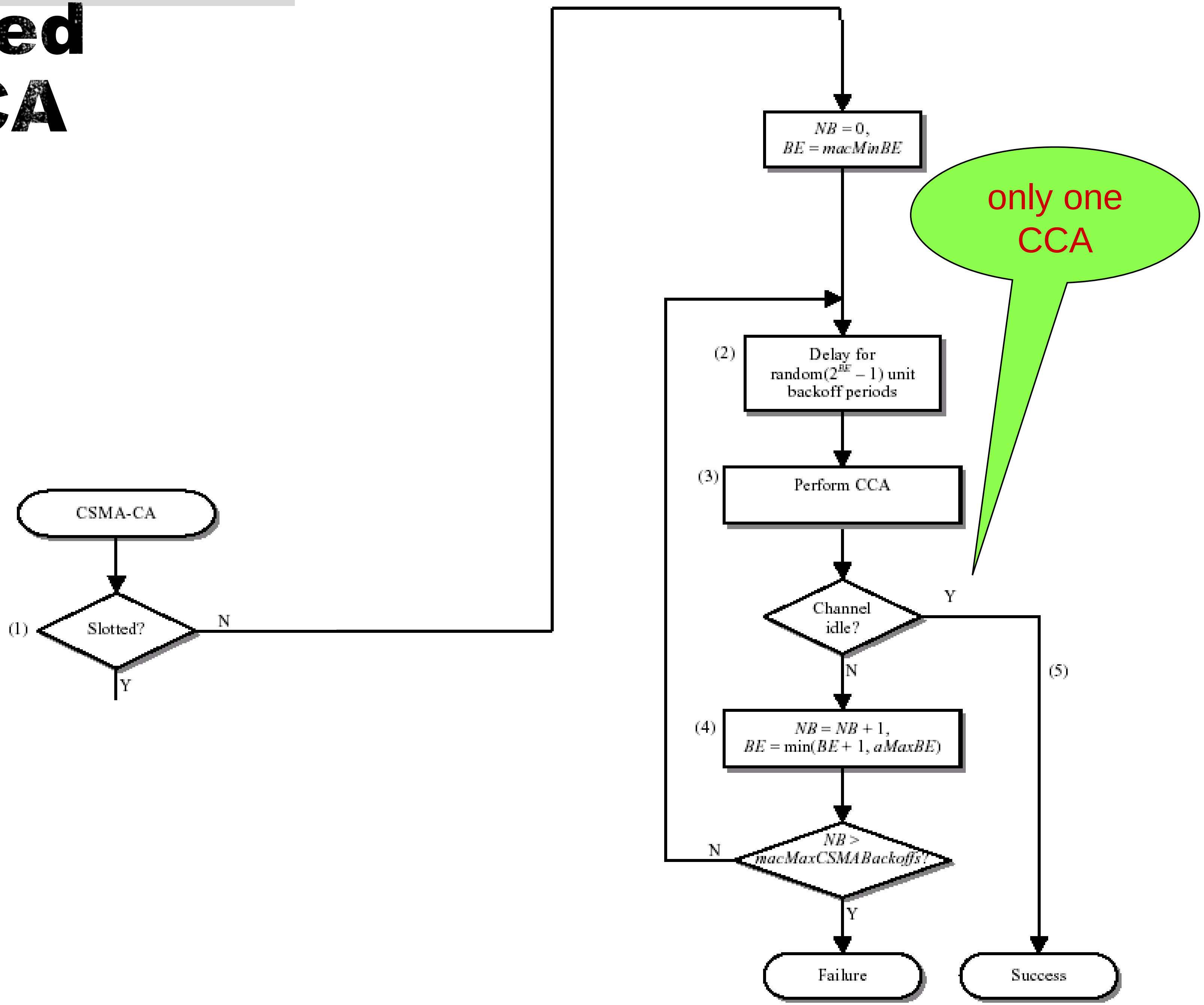
Why 2 CCAs? (Case 2)



Why 2 CCAs? (Case 3)



Unslotted CSMA/CA



GTS: Guaranteed Time Slot (1/3)

- GTS allows a device to operate on the channel within a portion of the superframe.
- GTSs should only be allocated by the PAN coordinator.
- PAN coordinator can allocated up to 7 GTS in a superframe.
- PAN coordinator decides whether to allocate GTS based on:
  - Requirements of the GTS request
  - The current available capacity in the superframe

GTS: Guaranteed Time Slot (2/3)

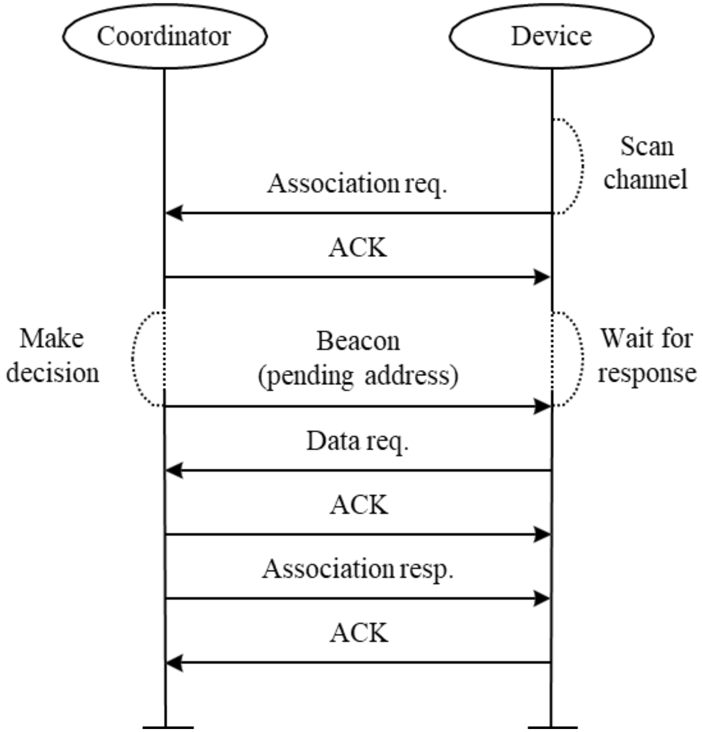
- GTS can be also freed:
  - At any time at the discretion of PAN coordinator.
  - By the device that originally requested GTS.
- A device that has been allocated a GTS may also operate in contention access period (CAP).
- A data frame transmitted in an allocated GTS should use only short addressing.

GTS: Guaranteed Time Slot (3/3)

- Before GTS starts, the GTS direction should be specified as either transmitting or receiving.
- Each device may request 1 transmitting GTS and/or 1 receiving GTS.
- A device should only attempt to allocate and use a GTS if it is currently tracking the beacon.
  - If a device loses synchronization with PAN coordinator, all of its GTS allocations are lost.
- The use of GTSs by an reduced function device (RFD) is optional.

Association Procedure (1/2)

- A device becomes a member of a PAN by associating with its coordinator.
- Procedure:



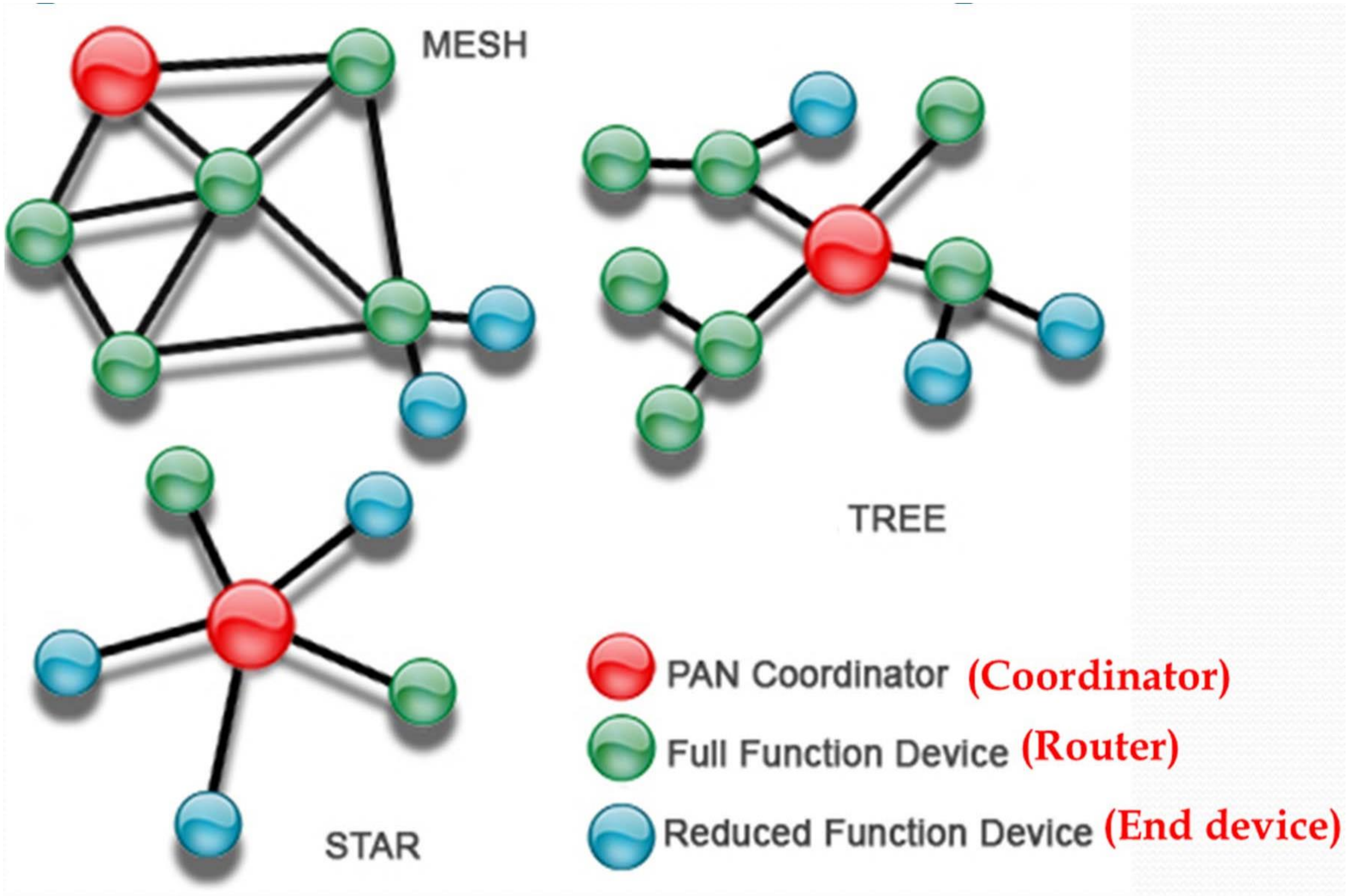
Association Procedure (2/2)

- In IEEE 802.15.4, association results are announced in an indirect fashion.
  - A coordinator responds to association requests by appending devices' long addresses in beacon frames.
- Devices need to send a data request to the coordinator to acquire the association result.
- After associating to a coordinator, a device will be assigned a 16-bit short address.

Outline

- ZigBee vs. IEEE 802.15.4
- IEEE 802.15.4: Physical layer
- IEEE 802.15.4: MAC layer
- ZigBee: Network layer

ZigBee Network Topologies



ZigBee Devices

- ZigBee defines three types of devices:
  - Coordinator: Responsible for initializing, maintaining, and controlling the network
  - Router: Form the network backbone.
  - End device: Only connect to a router or the coordinator.
- In a star or tree network, the coordinator (and routers) can announce beacons.
- In a mesh network, there is no regular beacon.
  - Devices in a mesh network can only communicate with each other in a peer-to-peer manner.

Address Assignment (1/2)

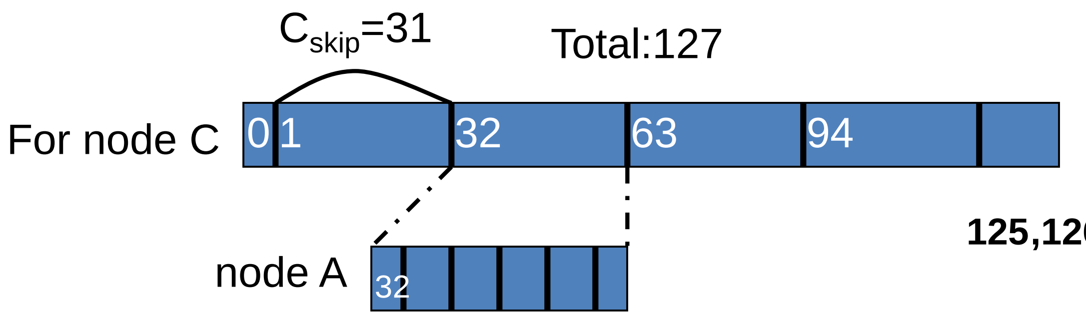
- In ZigBee, network addresses are assigned to devices by a distributed address assignment scheme.
- ZigBee coordinator decides three network parameters:
  - Maximum number of children (C_m) of a ZigBee router
  - Maximum number of child routers (R_m) of a parent node
  - Network depth (L_m)
- A parent device uses C_m, R_m, and L_m to obtain a parameter called C_{skip}, which is used to compute the size of its children's address pool.

$$
Cskip(d) = \begin{cases} 1 + Cm \cdot (Lm - d - 1), & \text{if } Rm = 1 \quad \cdots\cdots\cdots\cdots(a) \\ \dfrac{1 + Cm - Rm - Cm \cdot Rm^{Lm-d-1}}{1 - Rm}, & \text{Otherwise} \quad \cdots\cdots\cdots\cdots(b) \end{cases}
$$

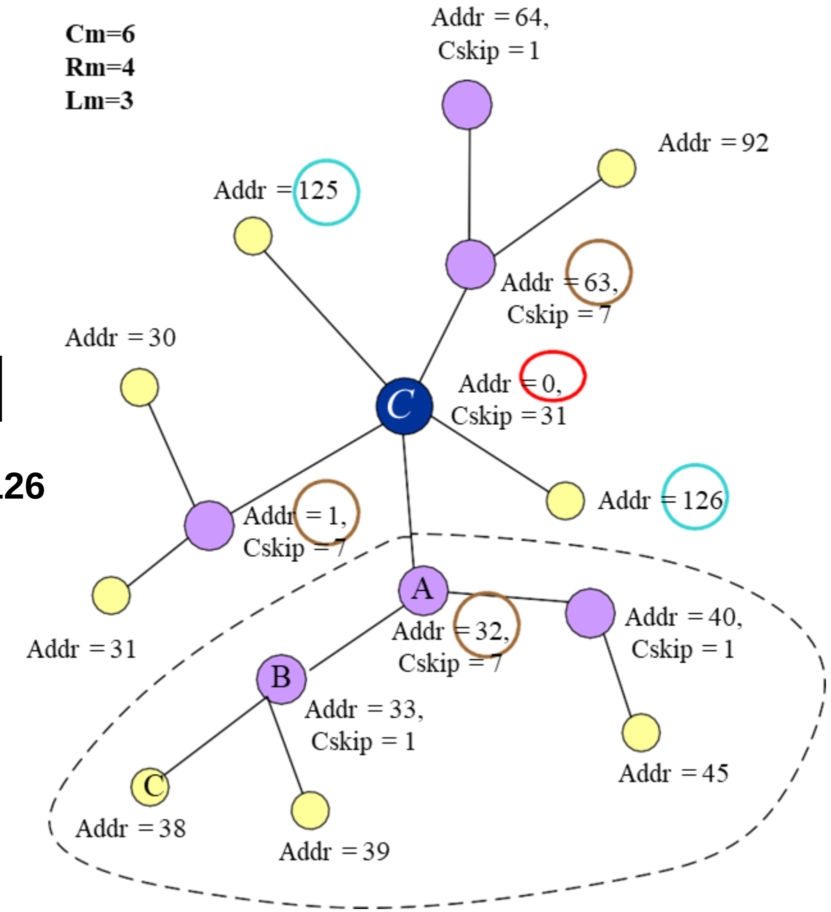
Address Assignment (2/2)

- Suppose that a parent node at network depth d has an address A_{parent}.
- Its n-th child router is assigned to address:
  - $A_{parent} + (n - 1) \times C_{skip}(d) + 1$
- Its n-th child end device is assigned to address:
  - $A_{parent} + R_m \times C_{skip}(d) + n$

Example of Address Assignment



125,126

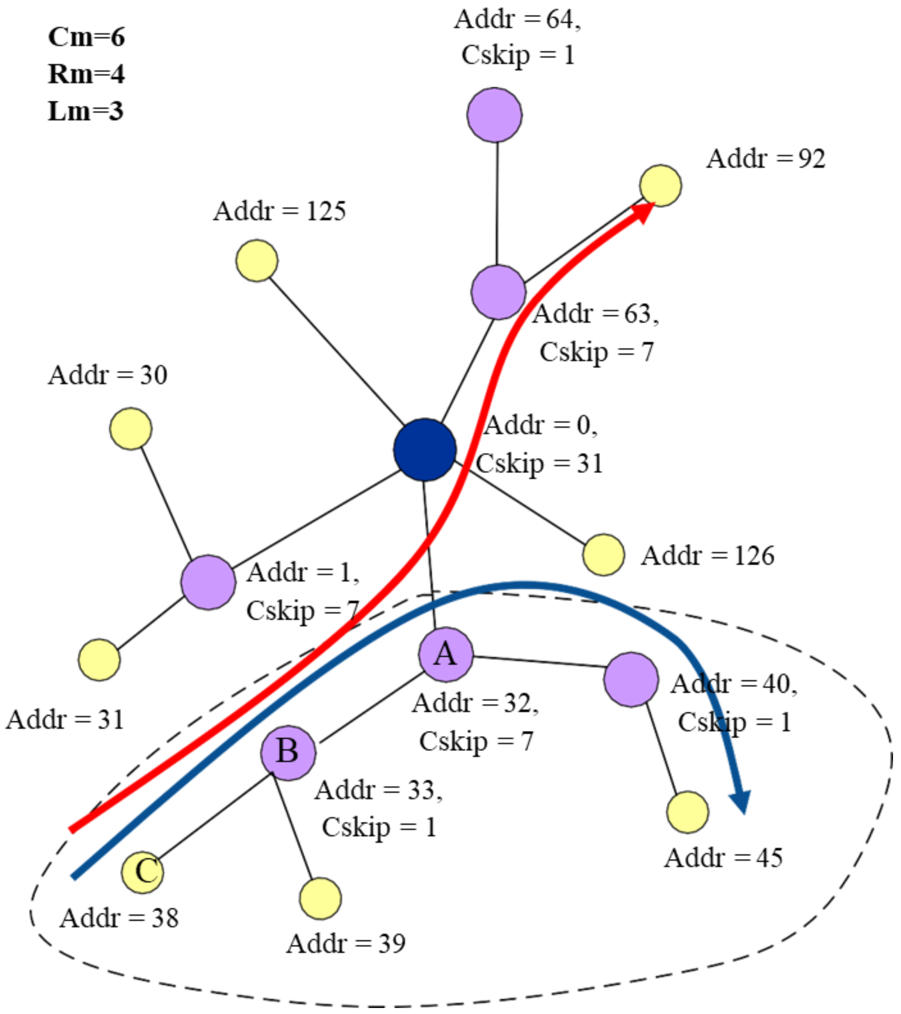


ZigBee Routing Strategies

- In a tree network:
  - Use the address assignment to obtain the routing paths.
- In a mesh network:
  - ZigBee coordinators and routers are said to have routing capacity if they have routing-table capacities and route-discovery-table capacities.
  - There are two options:
    - Reactive routing: Use when the device has the routing capacity.
    - Tree routing: Use when the device has no routing capacity.

Tree Routing

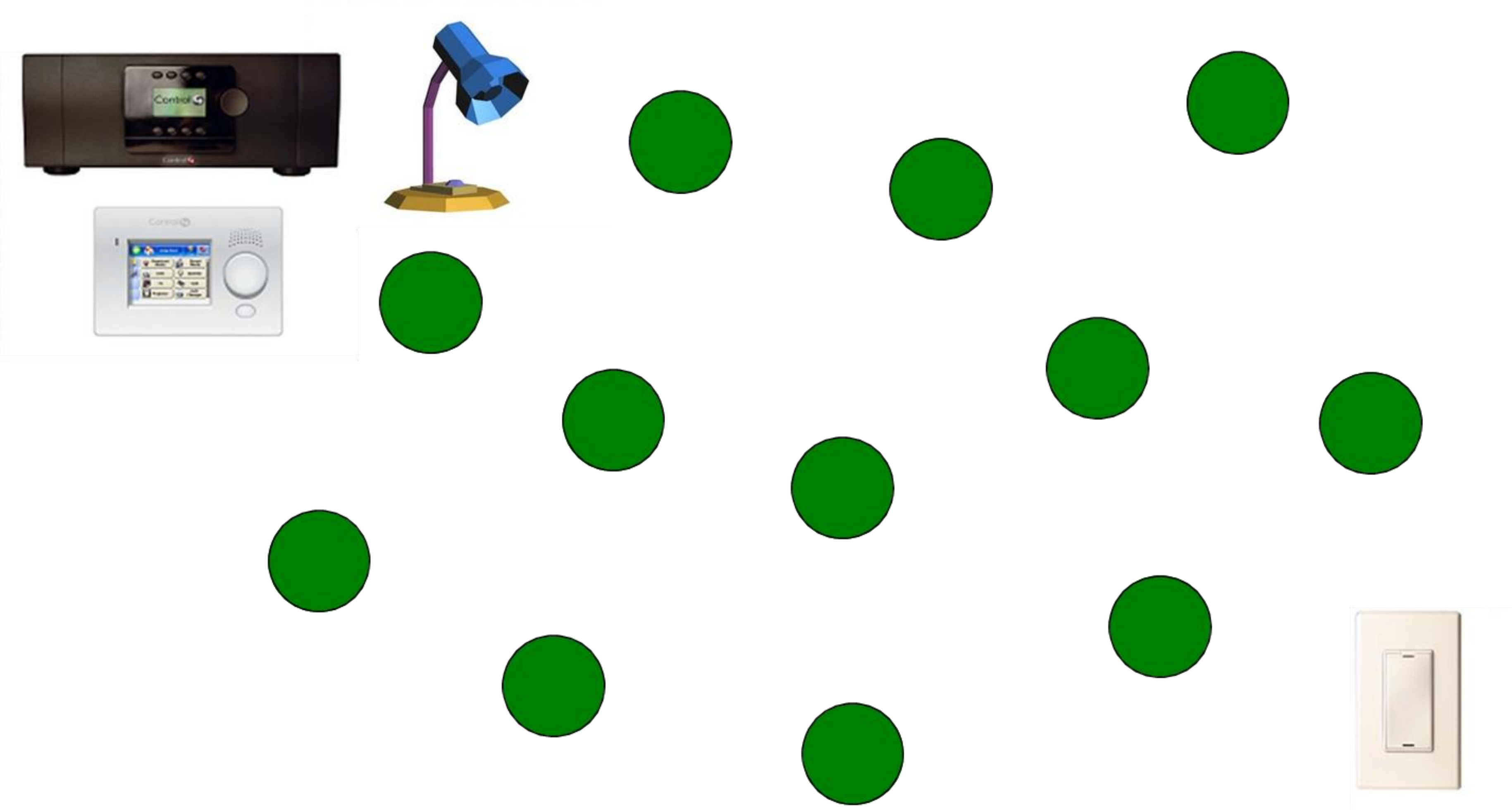
- When a device receives a packet, it first checks if it is the destination or one of its child end devices is the destination.
  - If so, accept the packet or forward it to a child.
  - Otherwise, relay it along the tree.
- Example:
  - Addr 38 (node C) -> Addr 45
  - Addr 38 (node C) -> Addr 92



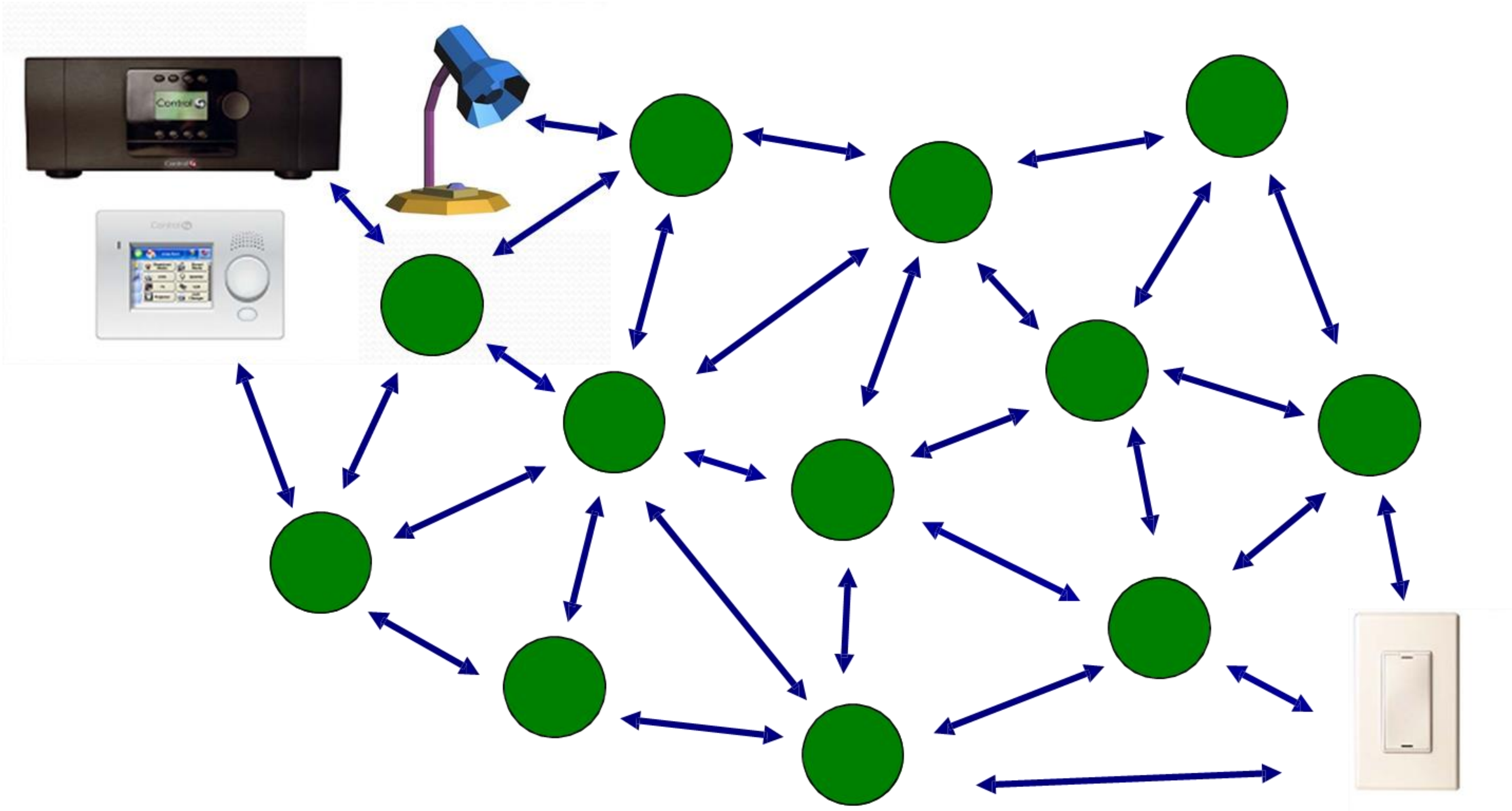
Mesh Routing

- Route discovery is done by AODV-like routing protocol.
  - The cost of a link is calculated by the packet delivery probability on that link.
- Route discovery procedure:
  - The source broadcasts a route request packet.
  - Intermediate nodes will rebroadcast the route request if they have routing-discovery-table capacities and the cost is lower.
    - Otherwise, these nodes will relay the request along the tree.
  - The destination will choose the routing path with the lowest cost and then send a route reply packet.

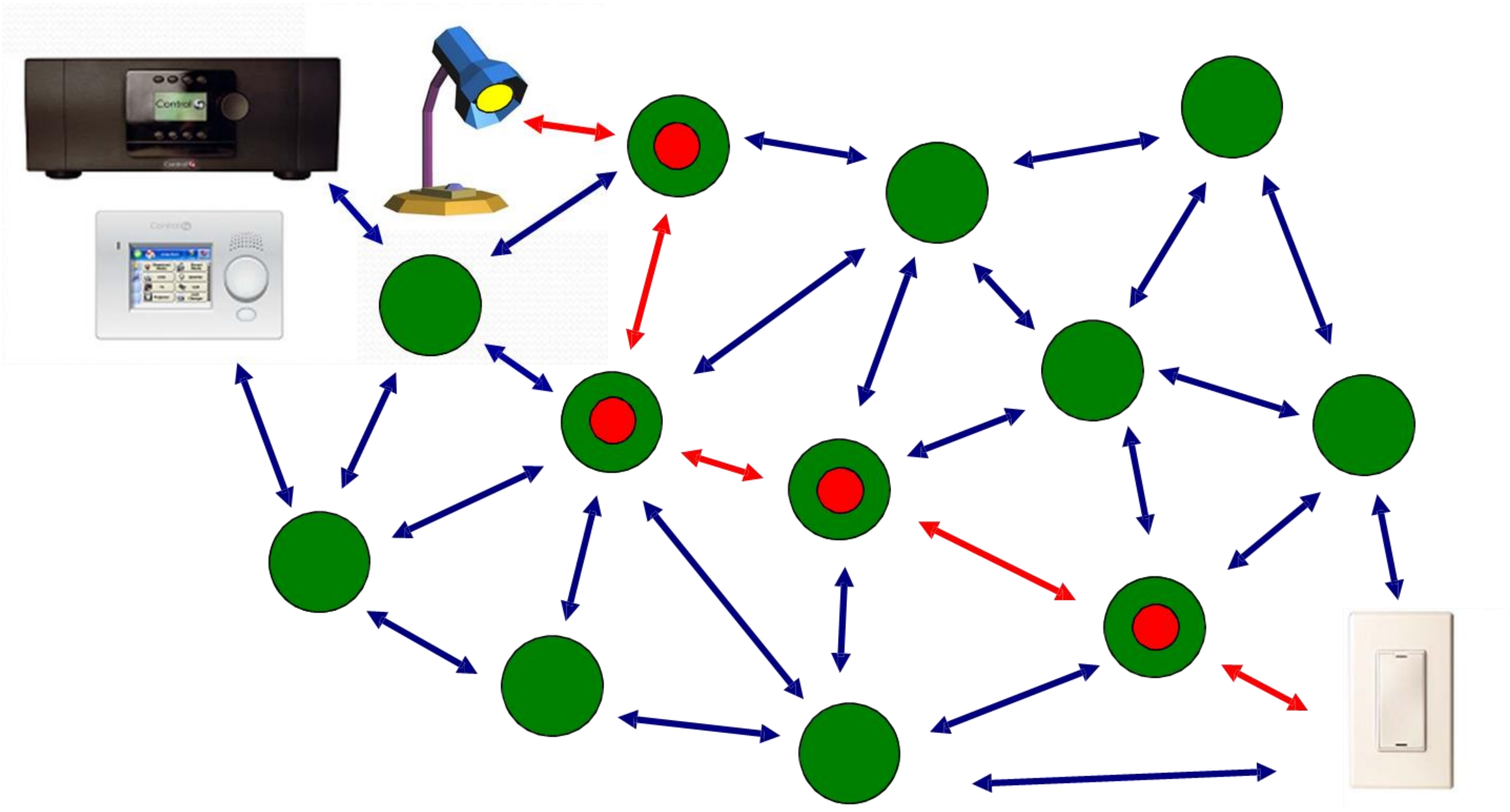
Example of Mesh Routing (1/5)



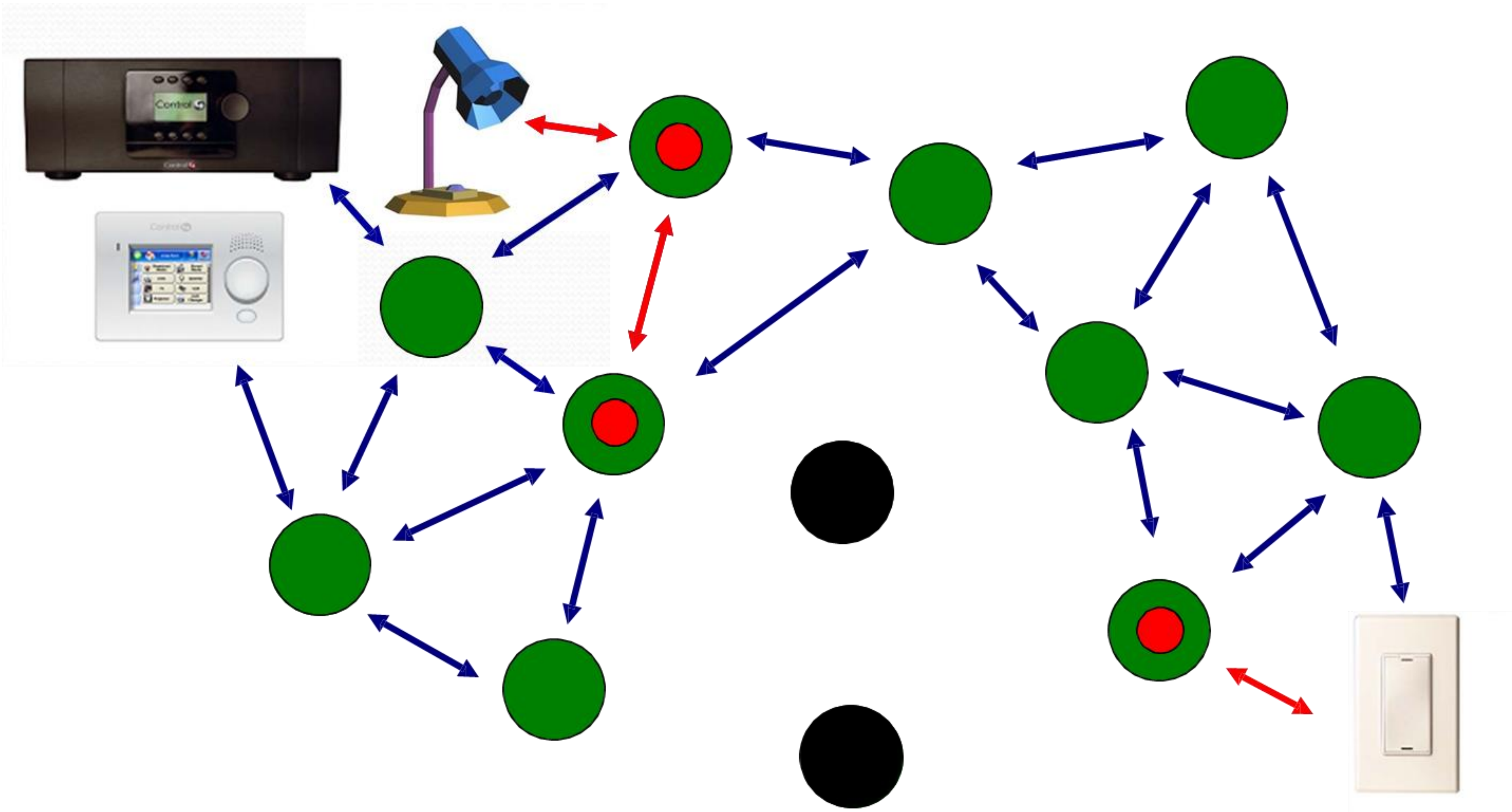
Example of Mesh Routing (2/5)



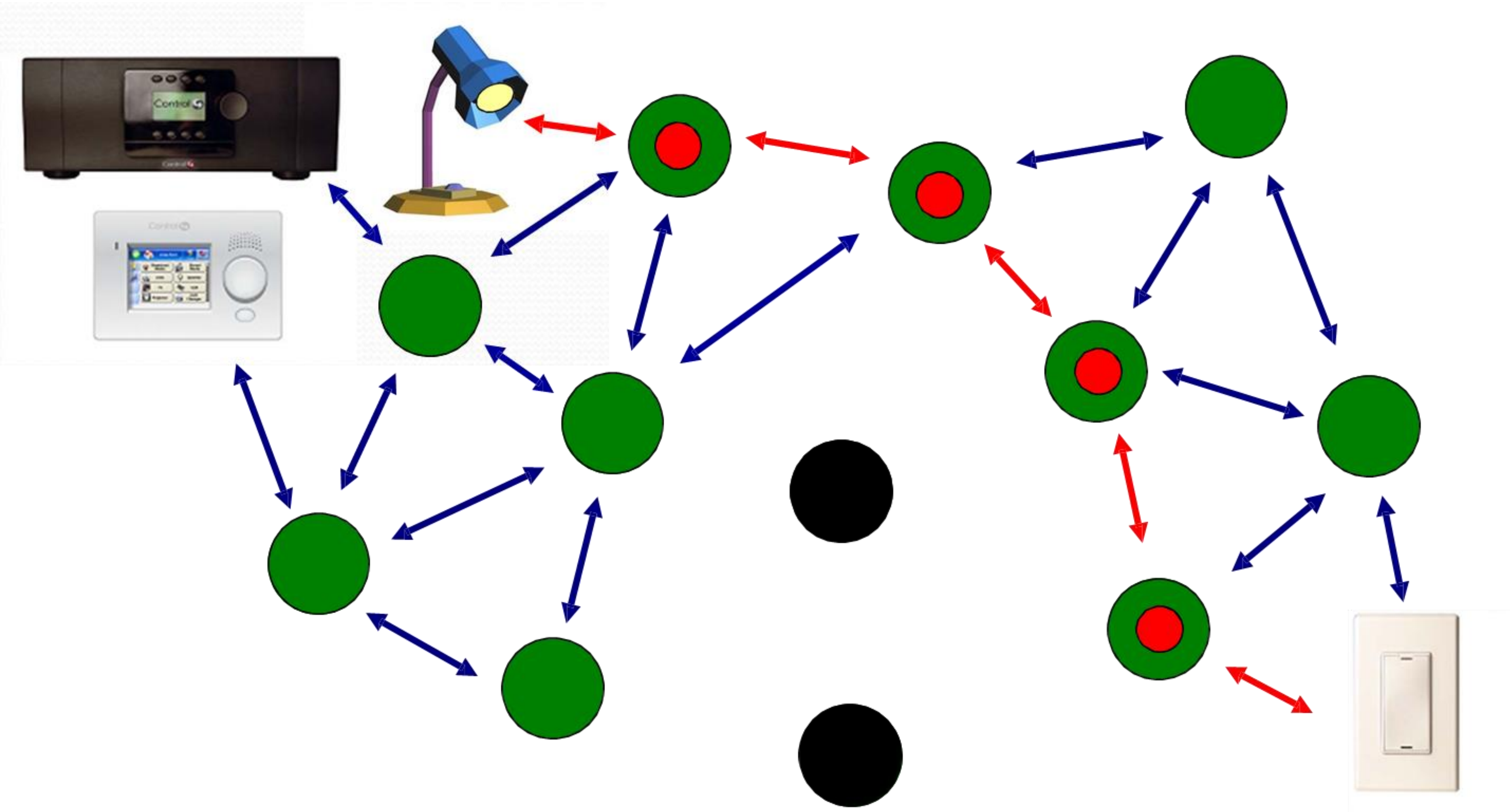
Example of Mesh Routing (3/5)



Example of Mesh Routing (4/5)



Example of Mesh Routing (5/5)



Comparison on Network Topologies

Topology	Advantages	Disadvantages
Star	1. Easy to synchronize 2. Support low power operation 3. Low latency	1. Small scale
Tree	1. Low routing cost 2. Can form superframes to support sleep mode 3. Allow multihop communication	1. Route reconstruction is costly 2. Latency may be quite long
Mesh	1. Robust multihop communication 2. Network is more flexible 3. Lower latency	1. Cannot form superframes (and thus cannot support sleep mode) 2. Route discovery is costly 3. Needs routing tables

Summary

- ZigBee is a standard created for control & sensor networks, which is developed by ZigBee alliance.
- ZigBee operates on the top of IEEE 802.15.4 to provide networking, security, and application software.
- IEEE 802.15.4 PHY operates on 868MHz/915MHz/2.4GHz.
- IEEE 802.15.4 supports slotted and unslotted CSMA/CA for beacon-enabled and non-beacon-enabled networks, respectively.
- ZigBee supports star, tree, and mesh network topologies, where the distributed address assignment scheme can help route packets in a tree network.