실시간 통신과 IoT

(CC533)

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(Department of Computer Science)

ZigBee / IEEE 802.15.4

WPAN

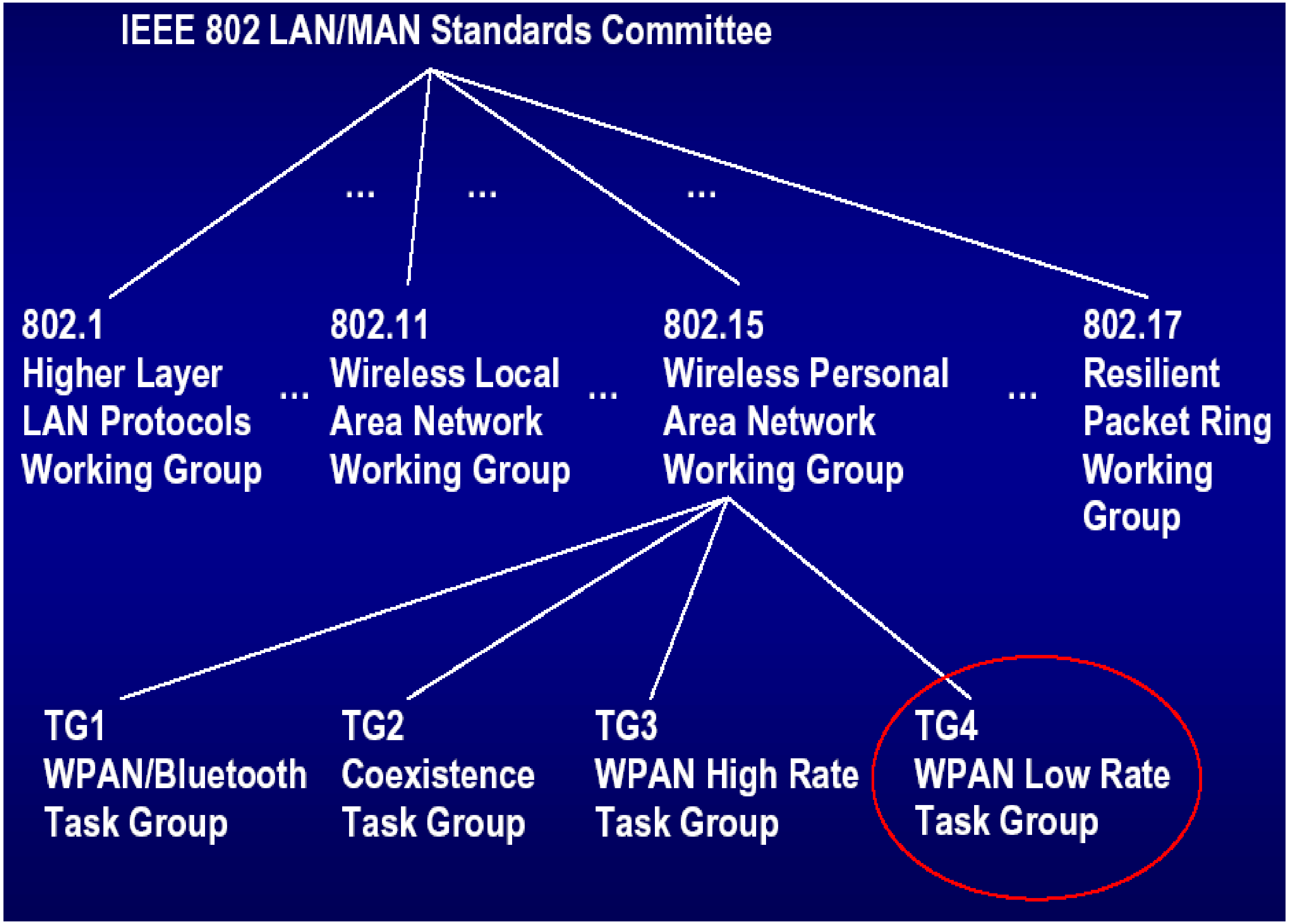
- **Wireless Personal Area Network (WPAN)**
  - Computer network used for communication among computer devices (e.g. smartphone) close to one person
  - Reach: A few meters
  - Use
    - Intrapersonal communication in devices
    - Connecting to a higher-level network and the Internet

A wireless PAN consists of a dynamic group of less than 255 devices that comm unicate within about a 33-foot range

WPAN

- **IEEE 802.15**
  - 15th working group of the IEEE 802
  - Specializes in Wireless PAN
  - It includes four task groups (numbered from 1 to 4)
- **ZigBee**
  - High level communication protocols based upon the specification produced by 802.15.4
    - IEEE 802.15.4 released in May 2003 for LR-WPAN

WPAN



IEEE 802 LAN/MAN Standards Committee
...
...
...
802.1
Higher Layer
LAN Protocols
Working Group
...
802.11
Wireless Local
Area Network
Working Group
...
802.15
Wireless Personal
Area Network
Working Group
...
802.17
Resilient
Packet Ring
Working
Group
TG1
WPAN/Bluetooth
Task Group
TG2
Coexistence
Task Group
TG3
WPAN High Rate
Task Group
TG4
WPAN Low Rate
Task Group

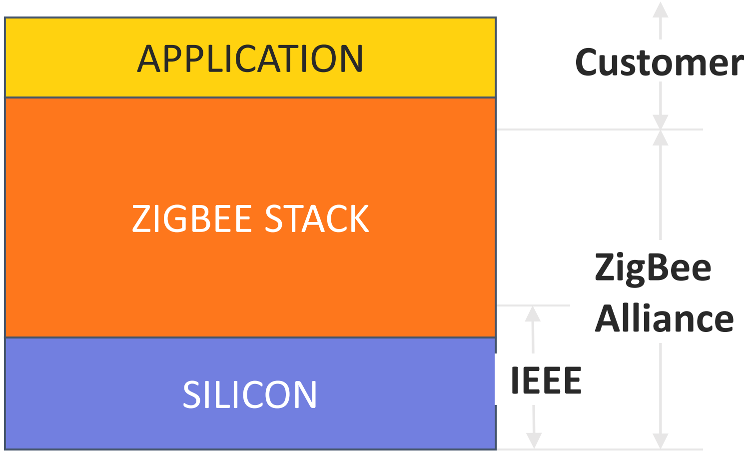
DEVELOPMENT OF THE STANDARD

IEEE 802.15.4 Working Group

- Defining lower layers of protocol stack: MAC and PHY
- Available today

ZigBee Alliance

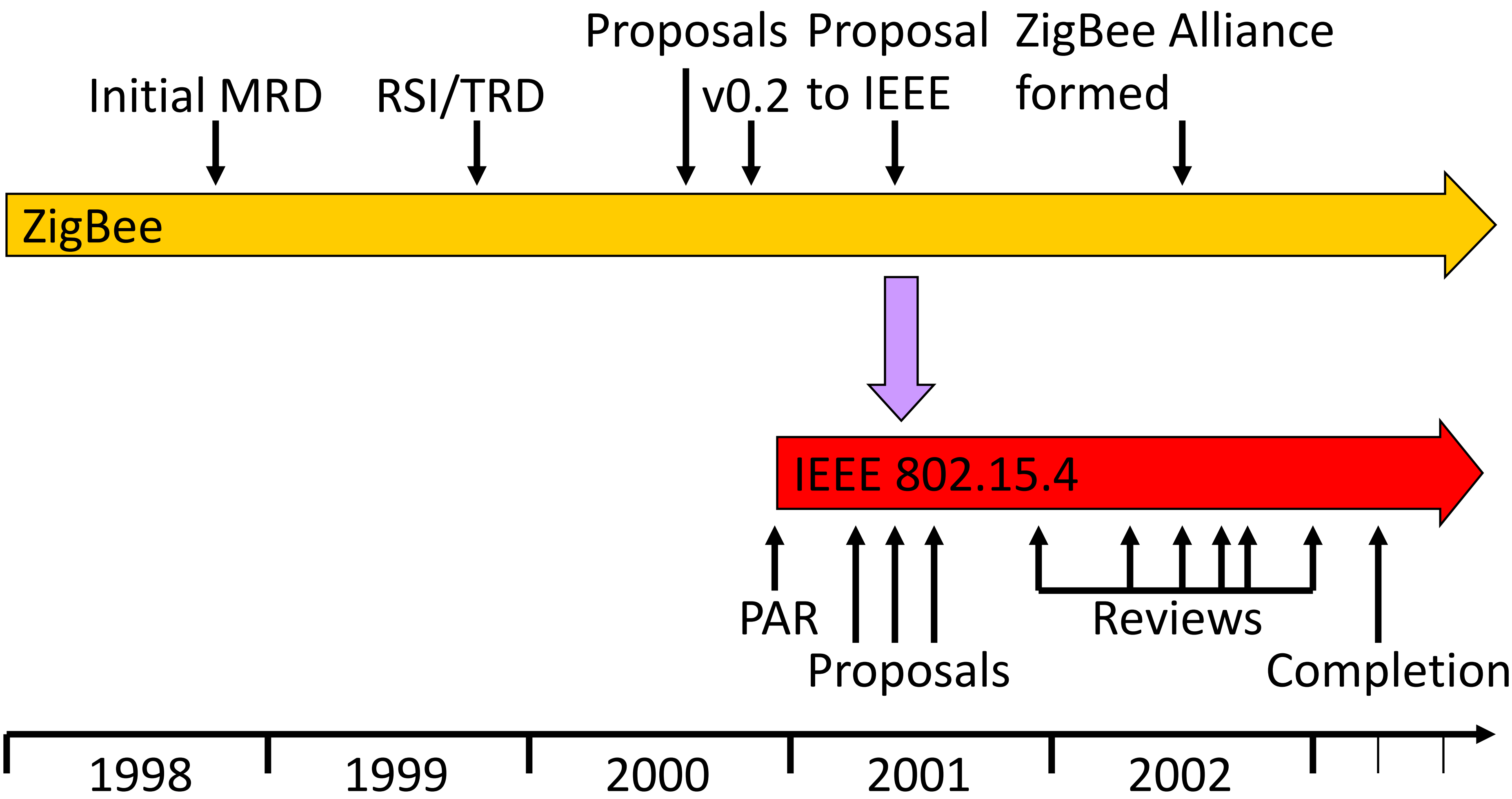
- 50+ companies: semiconductor manufacturers, IP providers, OEMs, etc.
- Defining upper layers of protocol stack
  - From network to application, including application profiles
- Initial draft available mid 2003



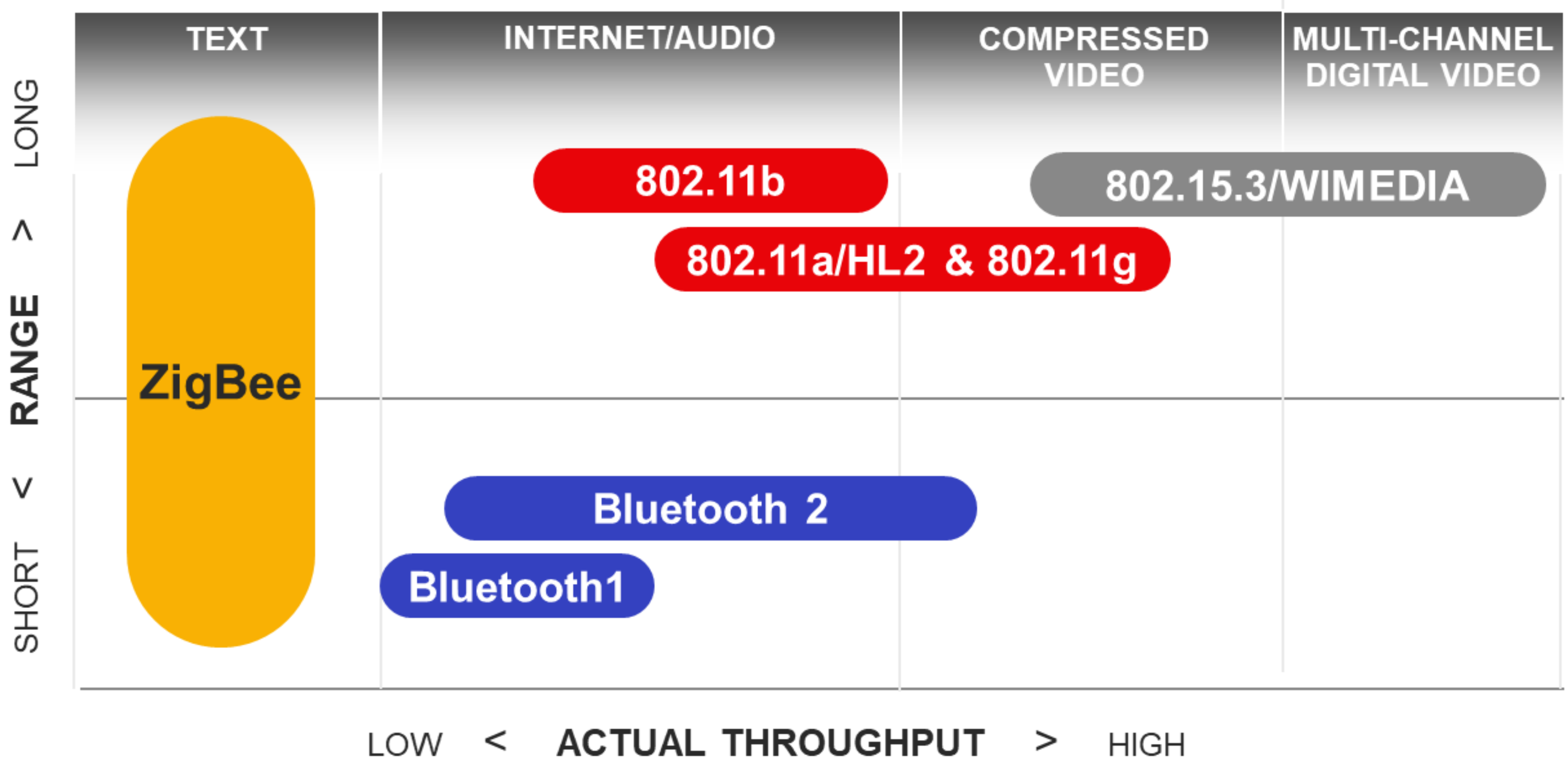
DEVELOPMENT OF THE STANDARD

- **Zigbee alliance solution**
  - Targeted at home and building automation and controls, consumer electronics, PC peripherals, medical monitoring, and toys
  - Industry standard through application profiles
  - Primary drivers are simplicity, long battery life, networking capabilities, reliability, and cost
  - Alliance provides interoperability and certification testing

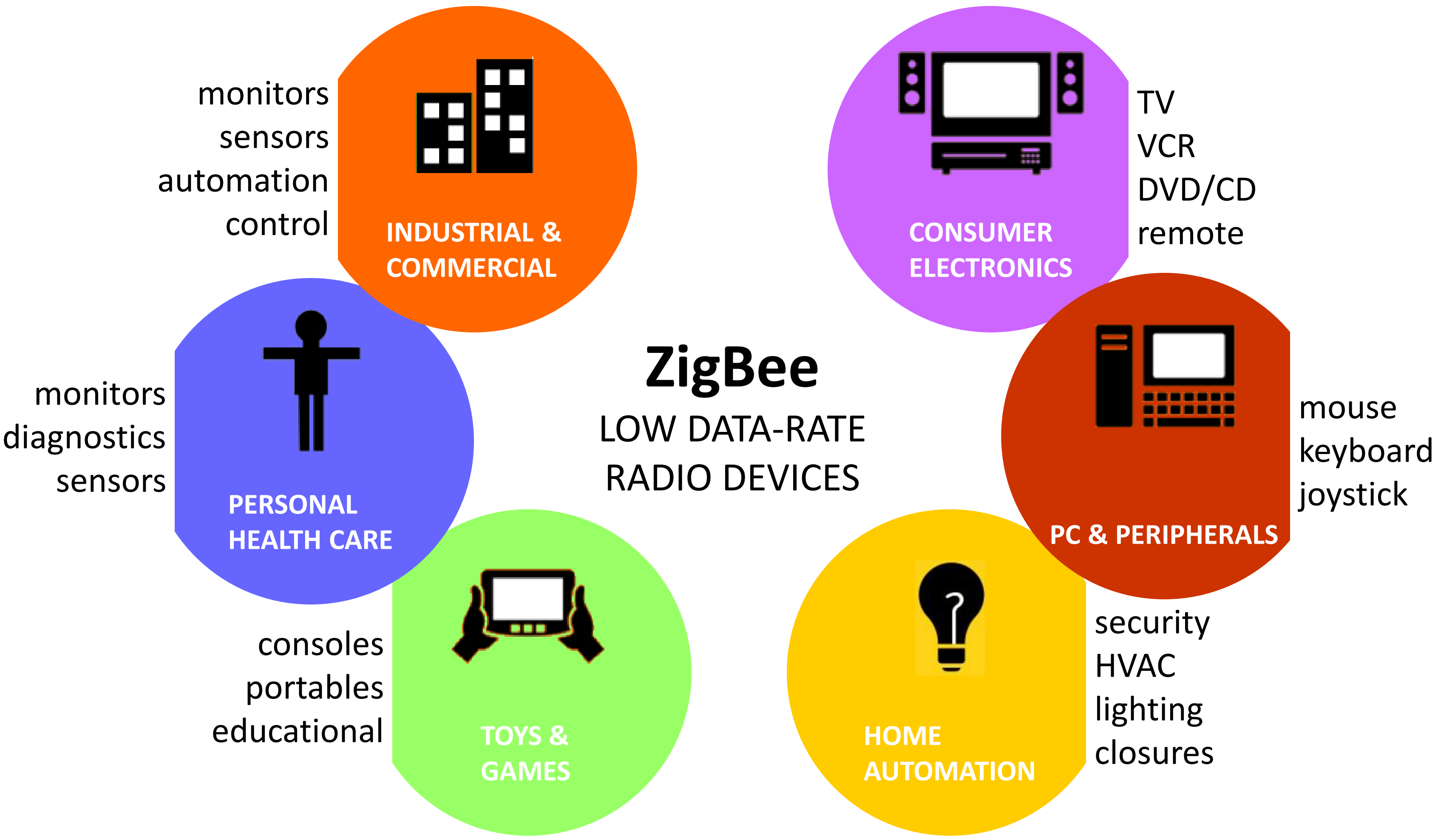
ZIGBEE HISTORY



WIRELESS MARKET



APPLICATIONS



MARKET REQUIREMENTS

- Global, license free ISM band operation
- Unrestricted geographic use
- RF penetration through walls & ceilings
- Automatic/semi-automatic installation
- Ability to add or remove devices
- Cost advantageous

MARKET REQUIREMENTS

- 10k-115.2kbps data throughput
- 10-75m coverage range
- Up to 65k slave nodes per network
- Up to 2 years of battery life on standard Alkaline batteries

IEEE 802.15.4 General Characteristics

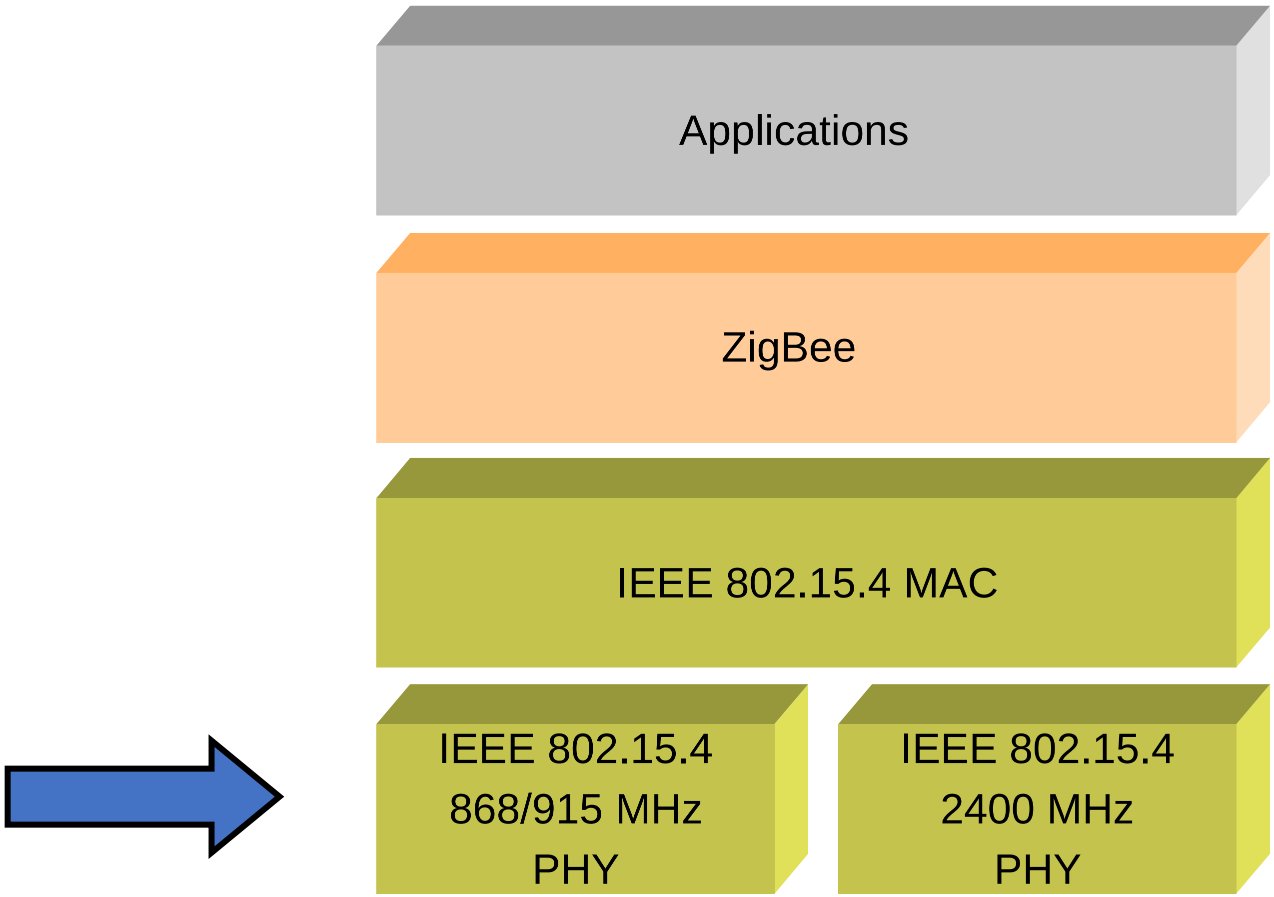
- **IEEE 802.15.4 Characteristics**
  - Data rates : 250 kb/s, 40 kb/s, 20 kb/s
  - Topology : Star or Peer-to-Peer
  - Low latency devices
  - Low power consumption
  - Frequency Bands of Operation
    - 16 channels in the 2.4GHz ISM band
    - 10 channels in the 915MHz ISM band
    - 1 channel in the European 868MHz band.

IEEE 802.15.4 General Characteristics

- **Frequencies and Data Rates**

	BAND	COVERAGE	DATA RATE	CHANNEL(S)
2.4 GHz	**ISM**	**Worldwide**	**250 kbps**	**11-26**
868 MHz		**Europe**	**20 kbps**	**0**
915 MHz	**ISM**	**Americas**	**40 kbps**	**1-10**

IEEE 802.15.4 / ZigBee Architecture



- **Packet generation**
- **Packet reception**
- **Data transparency**
- **Power Management**

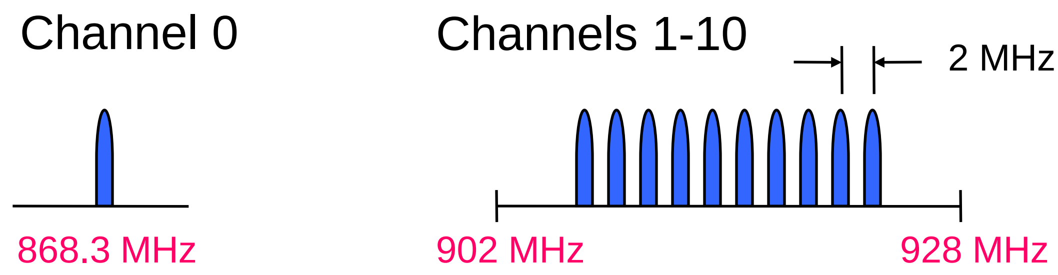
IEEE 802.15.4 PHY Overview

- **PHY functionalities:**
  - Activation and deactivation of the radio transceiver
  - Energy detection within the current channel
  - Link quality indication for received packets
  - Clear channel assessment for CSMA-CA
  - Channel frequency selection
  - Data transmission and reception

IEEE 802.15.4 PHY Overview

Operating Frequency Bands

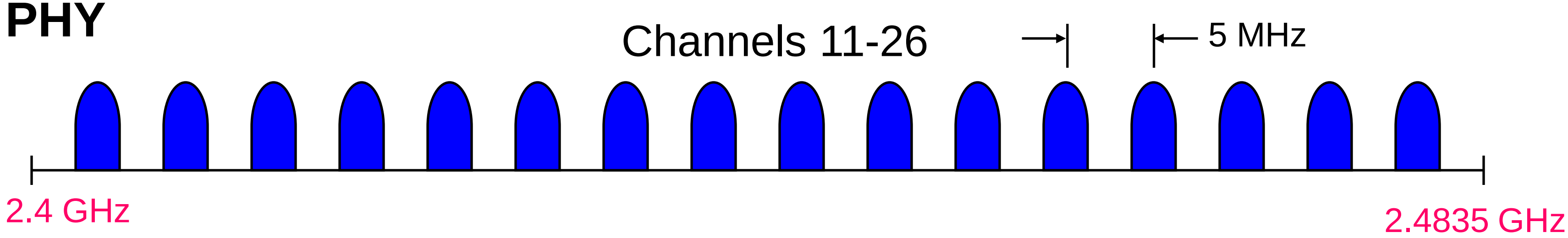
868MHz / 915MHz PHY



868 MHz/915 MHz direct sequence spread spectrum (DSSS) PHY (11 channels)

- 1 channel (20Kb/s) in European 868MHz band
- 10 channels (40Kb/s) in 915 (902-928)MHz ISM band

2.4 GHz PHY

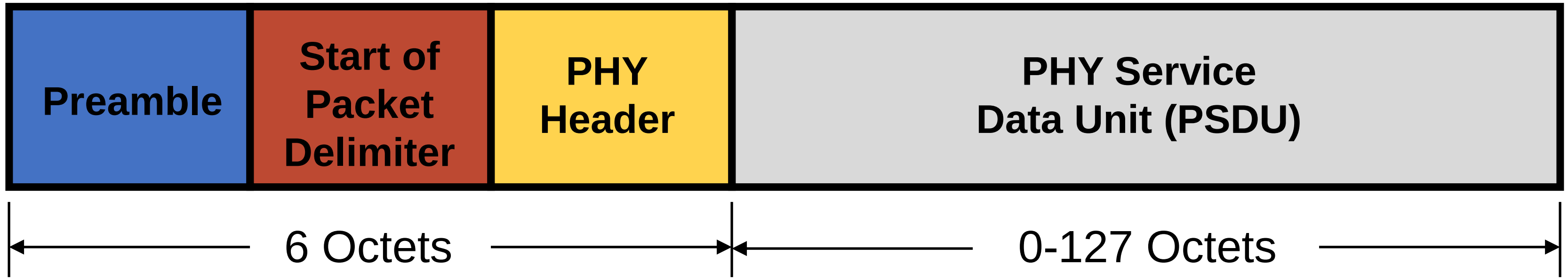


2450 MHz direct sequence spread spectrum (DSSS) PHY (16 channels)

- 16 channels (250Kb/s) in 2.4GHz band

IEEE 802.15.4 PHY Overview

- **Packet Structure**
  - PHY packet fields
    - Preamble (32 bits) : synchronization (all zero)
    - Start of Packet Delimiter (8 bits) : "11100101"
    - PHY Header (8 bits) – PSDU length
    - PSDU (PHY Service Data Unit) (0 to 1016 bits) – Data field



IEEE 802.15.4 PHY Overview

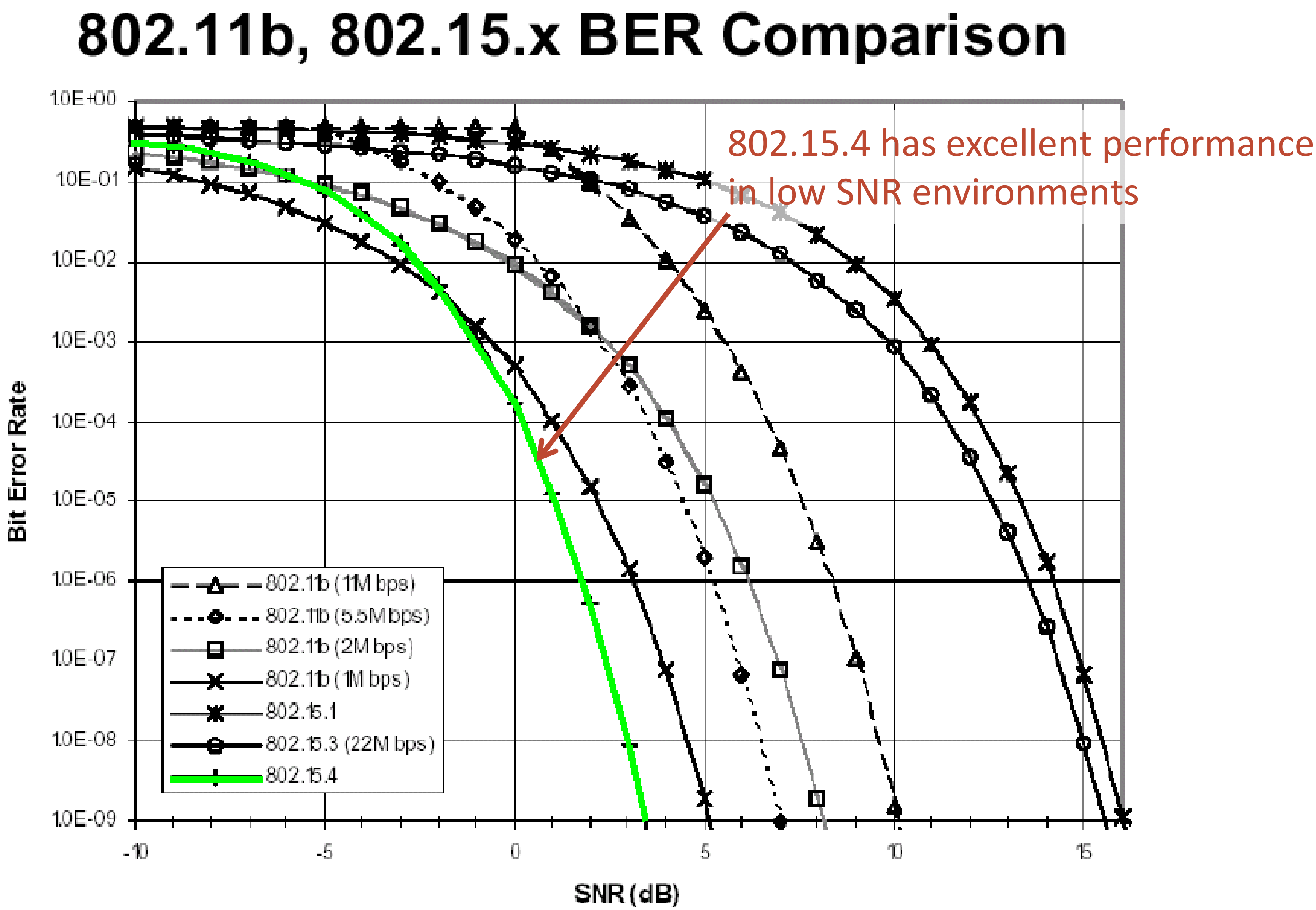
- **2.4 GHz PHY**
  - 250 kb/s (4 bits/symbol, 62.5 kBaud)
  - Data modulation is 16-ary orthogonal modulation
  - 16 symbols are orthogonal set of 32-chip PN codes
  - Chip modulation is O-QPSK at 2.0 Mchips/s

- **868MHz/915MHz PHY**
  - Symbol Rate
    - 868 MHz Band: 20 kb/s (1 bit/symbol, 20 kBaud)
    - 915 MHz Band: 40 kb/s (1 bit/symbol, 40 kBaud)
  - Data modulation is BPSK with differential encoding
  - Spreading code is a 15-chip m-sequence
  - Chip modulation is BPSK at
    - 868 MHz Band: 300 kchips/s
    - 915 MHz Band: 600 kchips/s

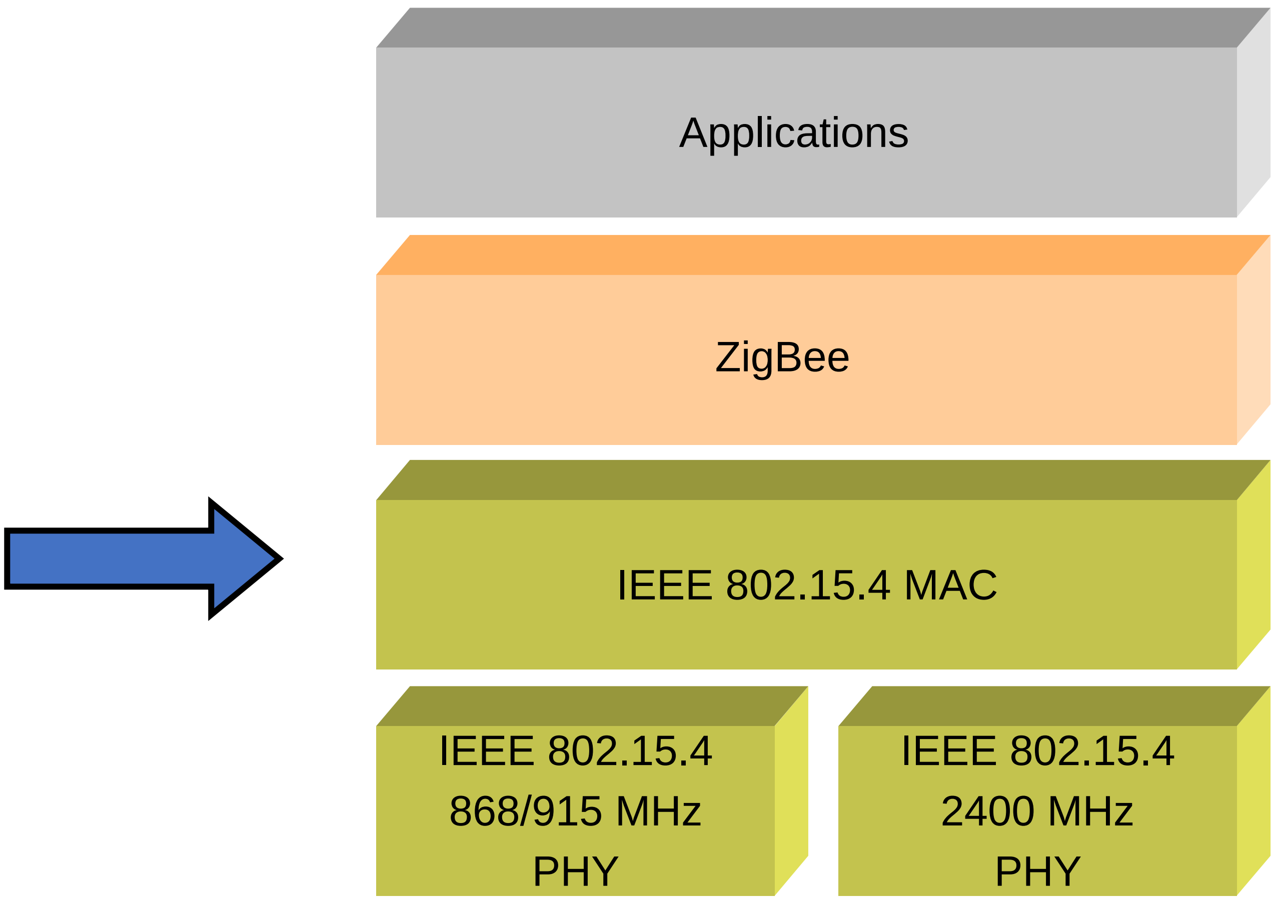
IEEE 802.15.4 PHY Overview

- **Transmit Power**
  - Capable of at least .5 mW
- **Transmit Center Frequency Tolerance**
  - ±40 ppm
- **Receiver Sensitivity (Packet Error Rate <1%)**
  - ≤ -85 dBm @ 2.4 GHz band
  - ≤ -92 dBm @ 868/915 MHz band
- **RSSI Measurements**
  - Packet strength indication
  - Clear channel assessment
  - Dynamic channel selection

IEEE 802.15.4 PHY Overview



IEEE 802.15.4 Architecture



- **Channel acquisition**
- **Contention mgt**
- **NIC address**
- **Error Correction**

IEEE 802.15.4 MAC Overview

MAC Characteristics

- Extremely low cost
- Ease of implementation
- Reliable data transfer
- Short range operation
- Very low power consumption
- 16-bit short addresses
- CSMA-CA channel access
- AES-128 security

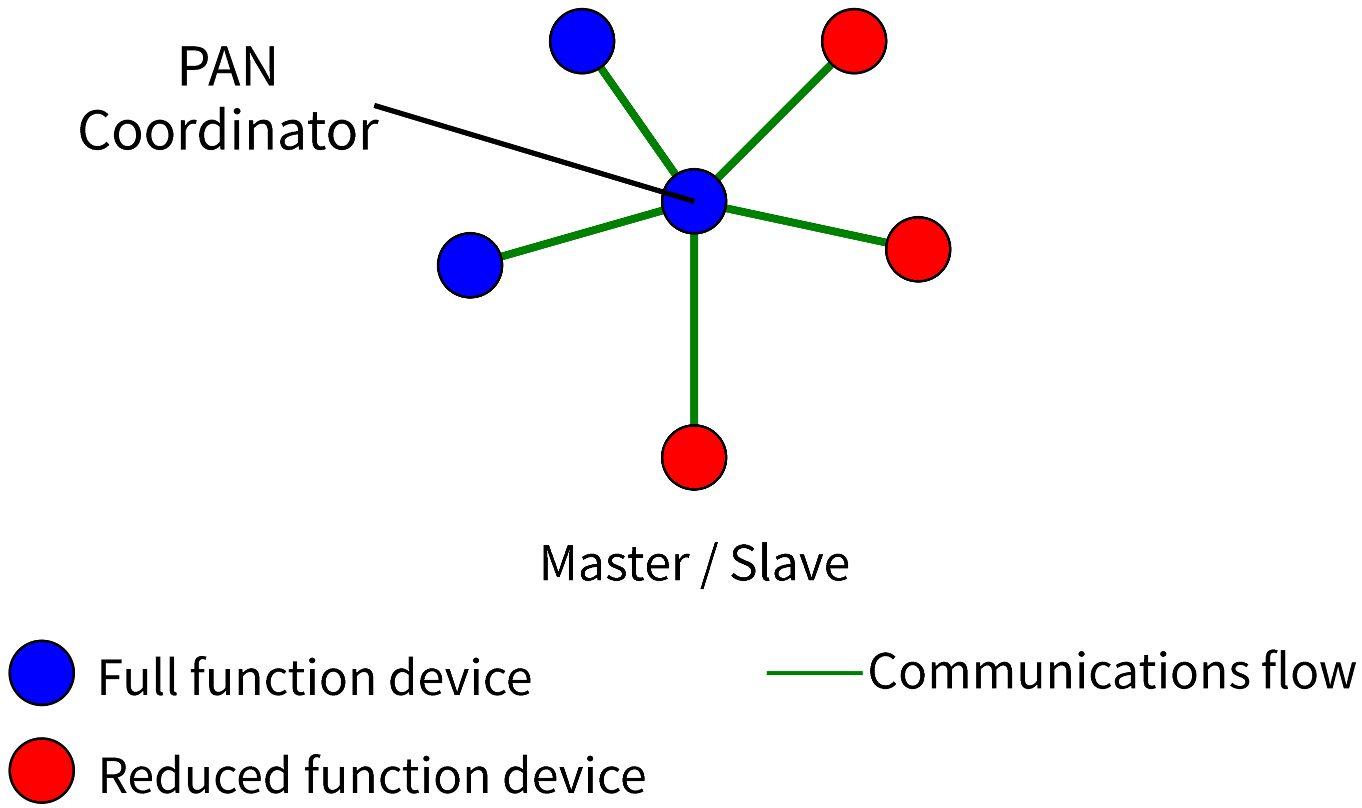
※ Simple but flexible protocol

IEEE 802.15.4 MAC Overview

- **Device Classes**
  - Full function device (FFD)
    - Any topology
    - Network coordinator capable
    - Talks to any other device
  - Reduced function device (RFD)
    - Limited to star topology
    - Cannot become a network coordinator
    - Talks only to a network coordinator
    - Very simple implementation

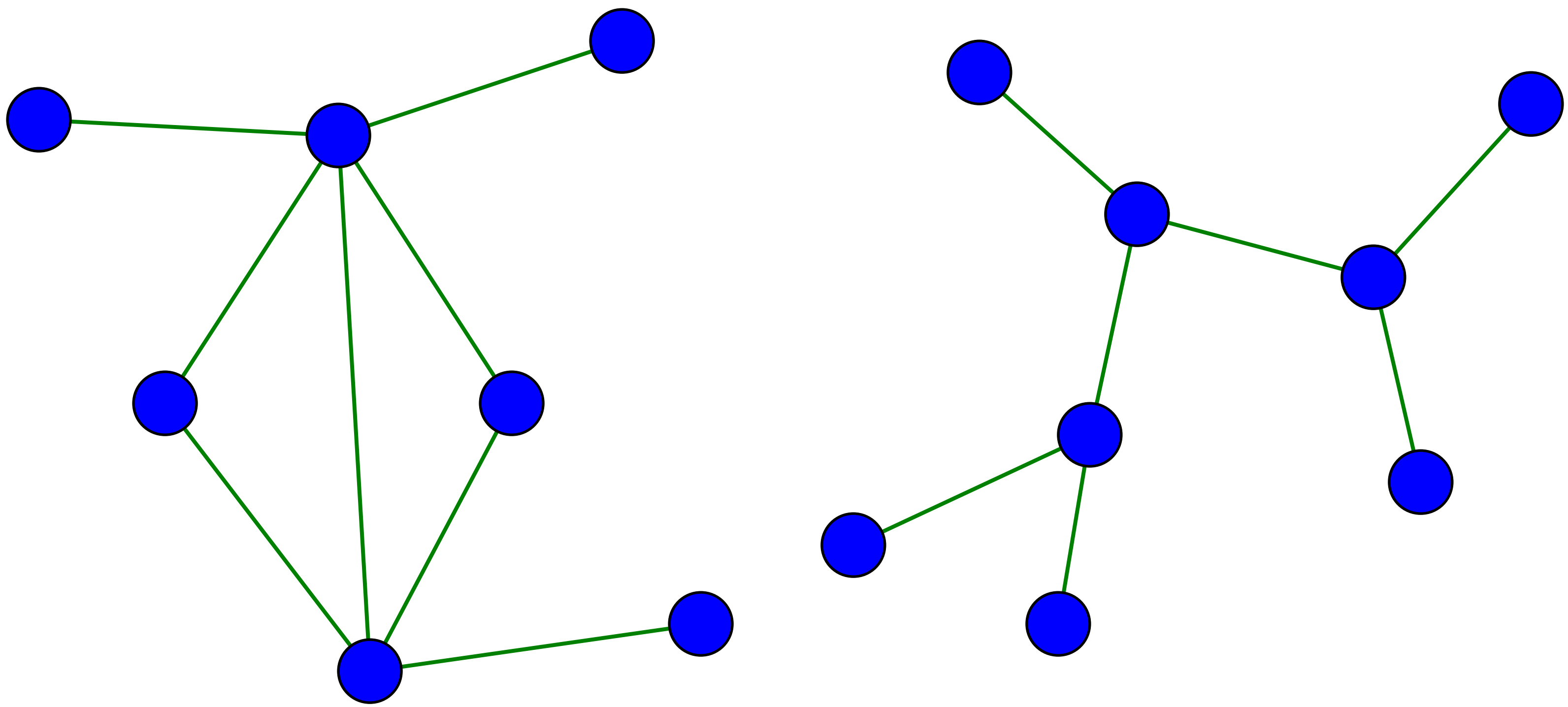
IEEE 802.15.4 MAC Overview

- **Network Topology**
  - Star topology



IEEE 802.15.4 MAC Overview

- Peer-Peer Topology



Point to point

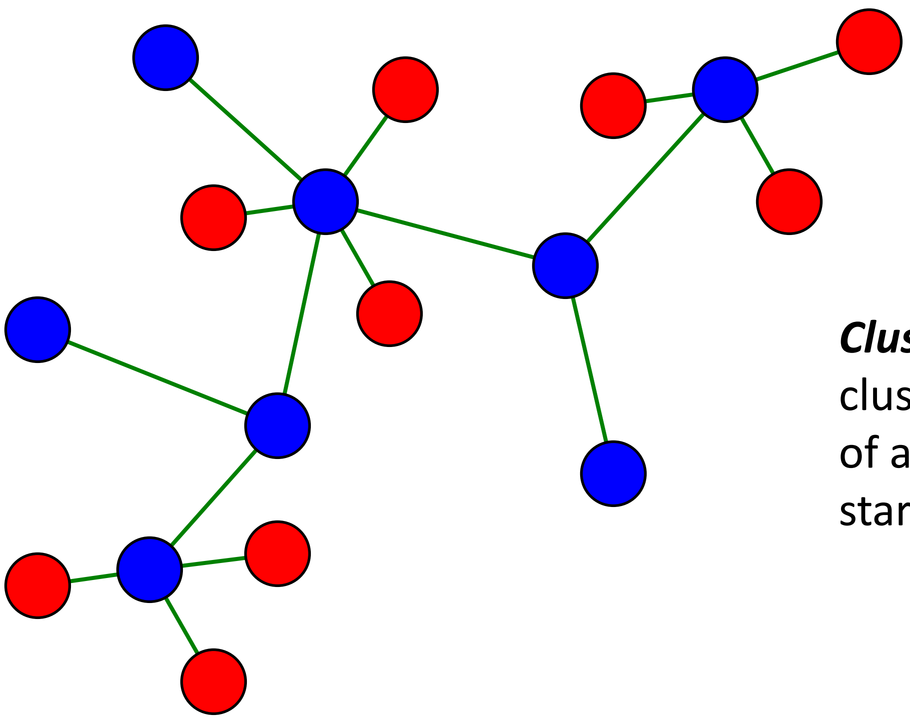
Cluster tree

Full function device

Communications flow

IEEE 802.15.4 MAC Overview

- Combined topology



Clustered stars - for example, cluster nodes exist between rooms of a hotel and each room has a star network for control.

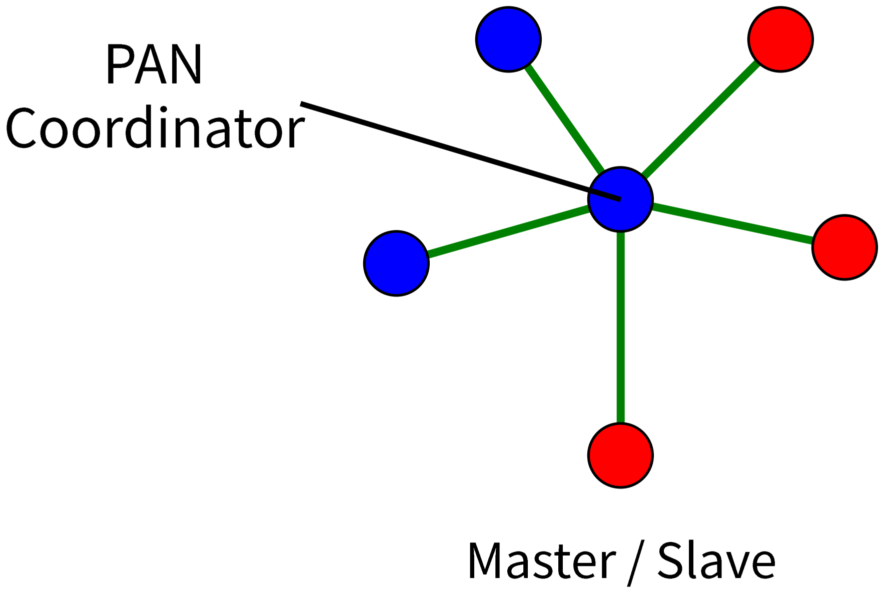
Full function device

Reduced function device

Communications flow

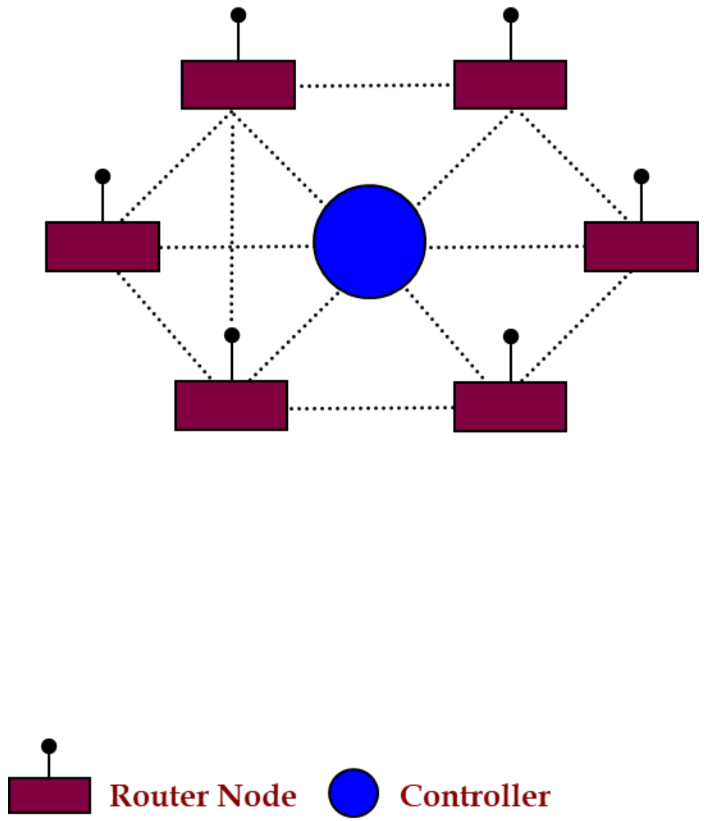
IEEE 802.15.4 MAC Overview

- **Star Network Key Attributes**
  - Simplicity
  - Low Cost
  - Long Battery Life
  - Single Point of Failure



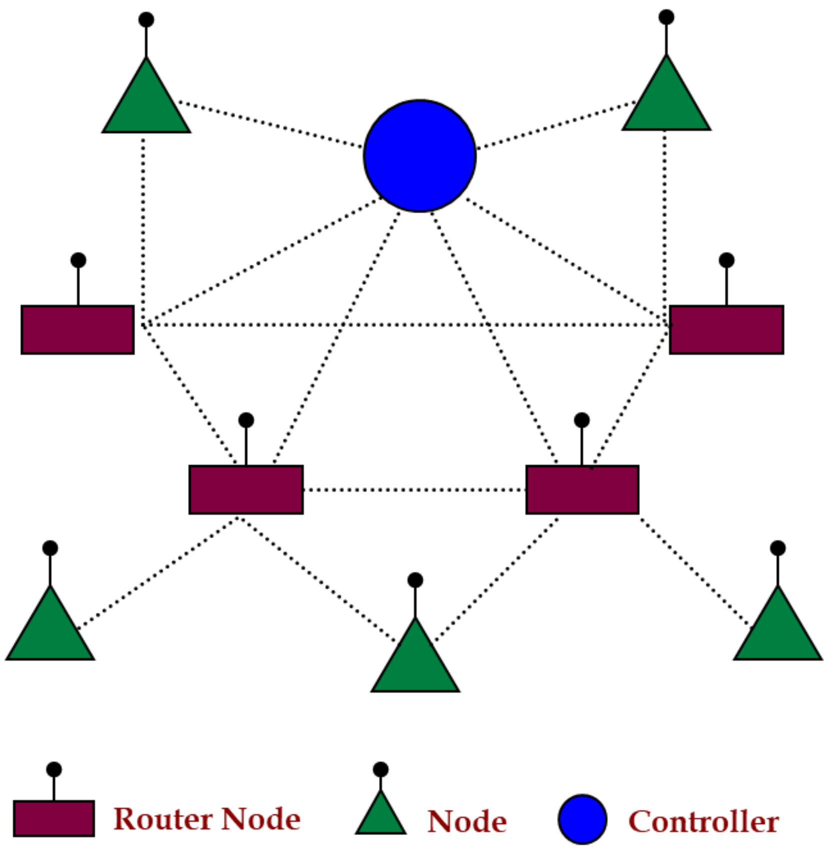
IEEE 802.15.4 MAC Overview

- **Mesh Network Key Attributes**
  - Reliability
  - Extended Range
  - No Battery Life
  - Routing Complexity



IEEE 802.15.4 MAC Overview

- **Hybrid Network Key Attributes**
  - Flexibility
  - Reliability/Range of Mesh
  - Battery Life of Star
  - Design Complexity

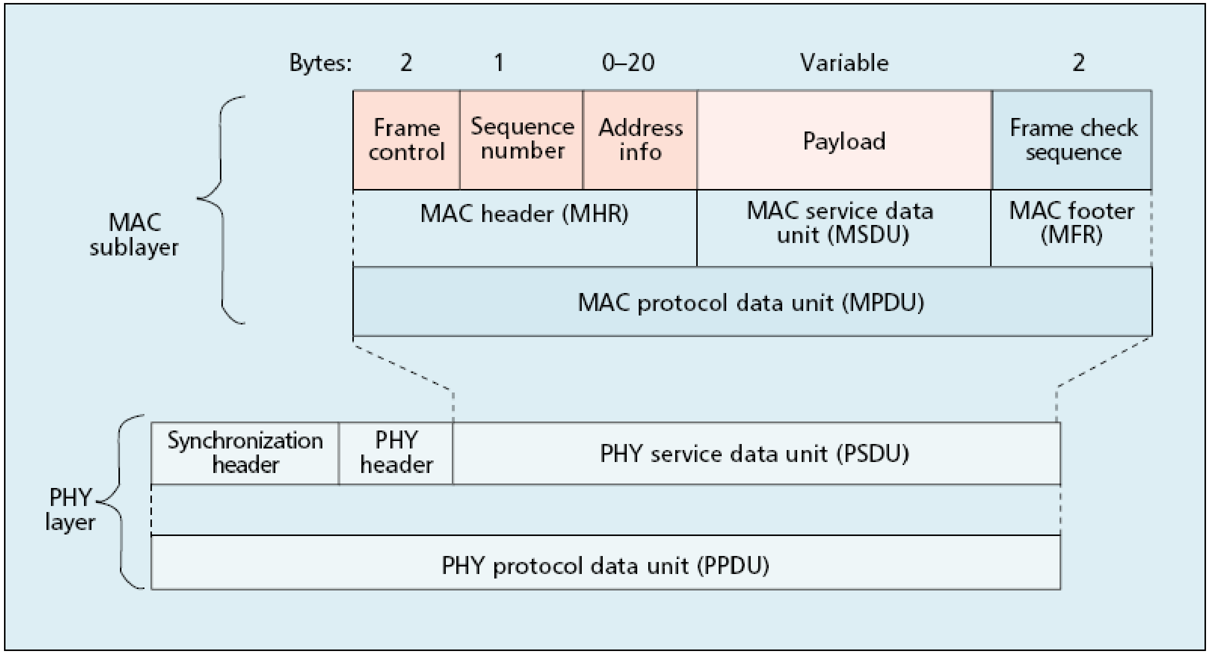


IEEE 802.15.4 MAC Overview

- **Device Addressing**
  - More than 2 devices on the same channel form a WPAN
    - WPAN must contain more than 1 FFD (Full Function Device, PAN coordinator)
    - Each independent PAN chooses unique PAN ID
  - Address types
    - 64-bit extended address
      - For direct communication in the PAN
    - 16-bit short address
      - Between a device and coordinator in the same PAN
      - Assigned by the coordinator
  - Devices can choose the address type

IEEE 802.15.4 MAC Overview

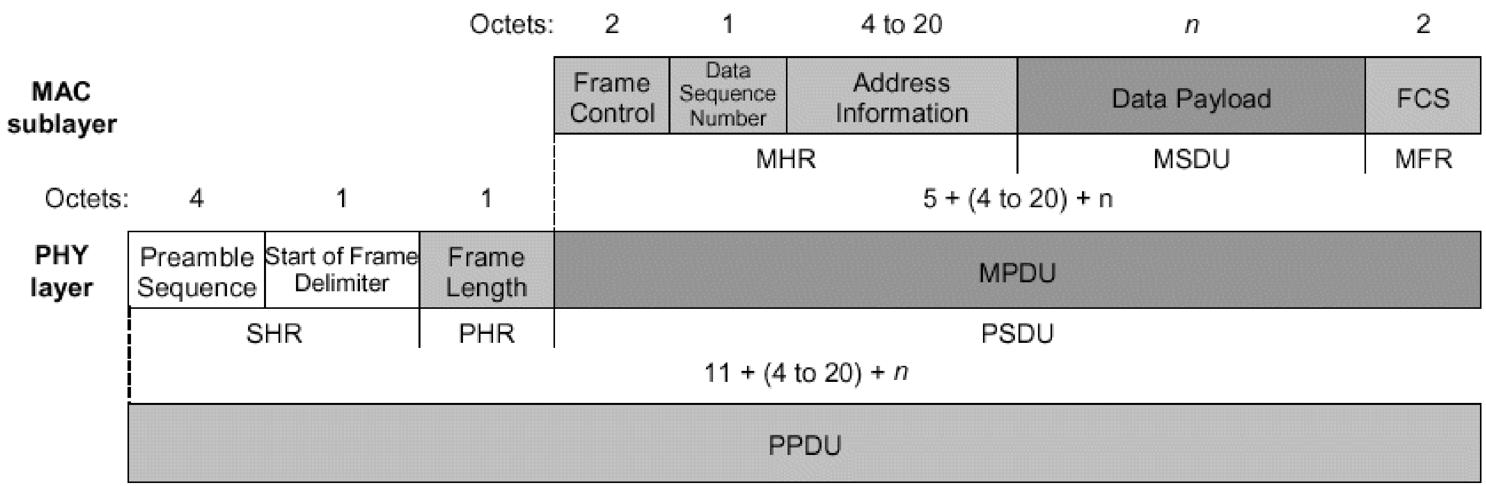
General Frame Structure



- 4 types of MAC frames
  - Data frame
  - Beacon frame
  - Acknowledgment Frame
  - MAC Command Frame

IEEE 802.15.4 MAC Overview

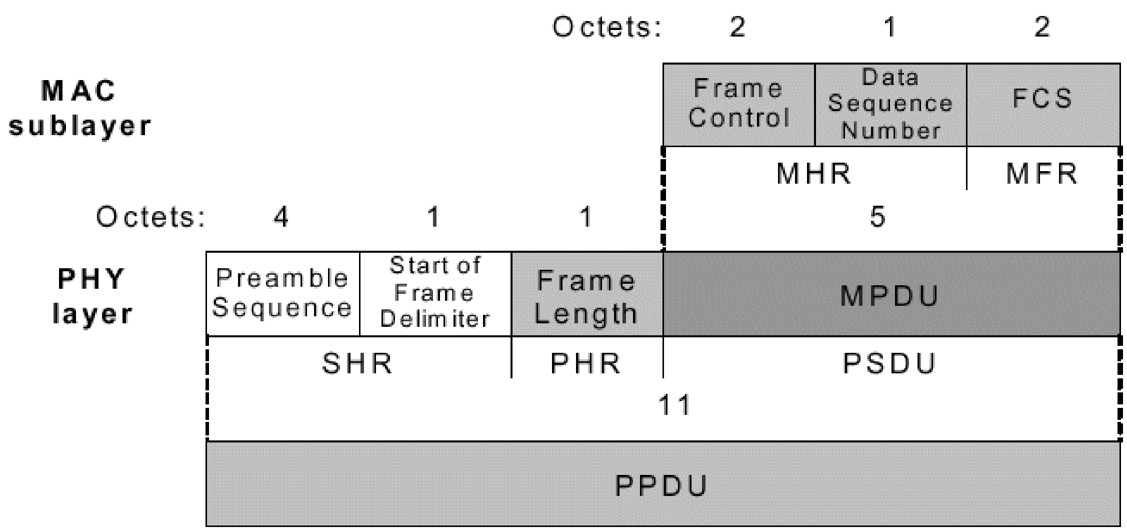
Data Frame Format



- Provides up to 104 byte data payload capacity
- Data sequence number to ensure that packets are tracked
- Frame Check Sequence (FCS) validates error-free data

IEEE 802.15.4 MAC Overview

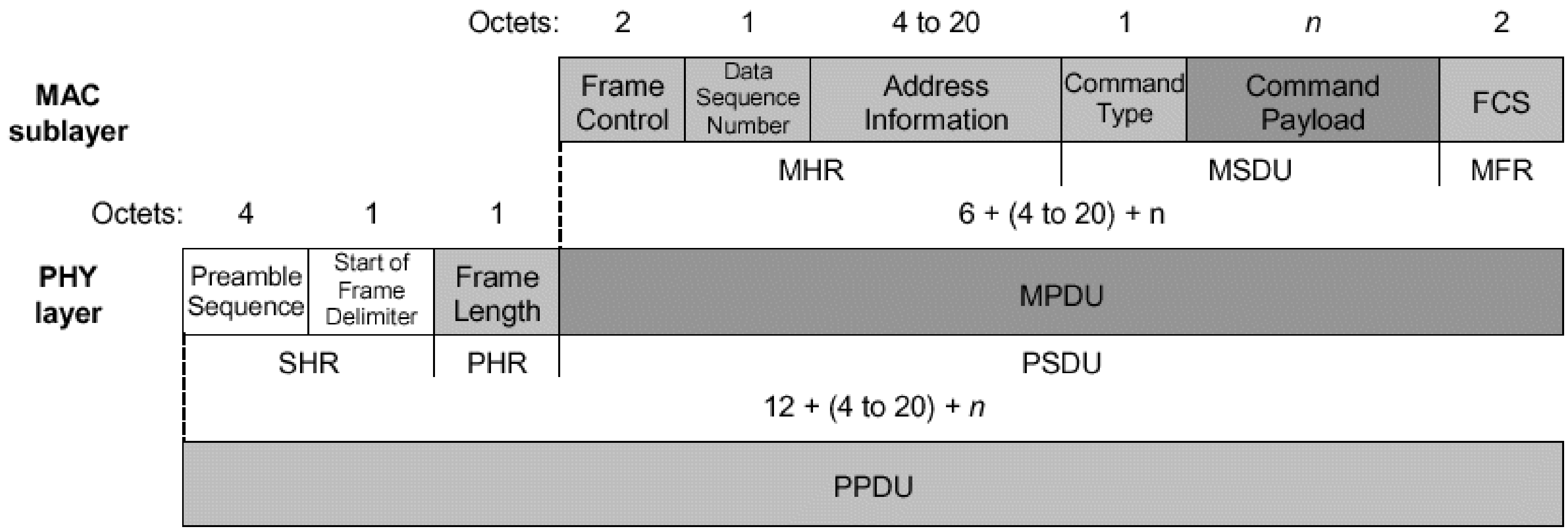
Acknowledgement Frame Format



- Active feedback from receiver to sender that packet was received without error
- Short packet that takes advantage of standards-specified "quiet time" immediately after data packet transmission

IEEE 802.15.4 MAC Overview

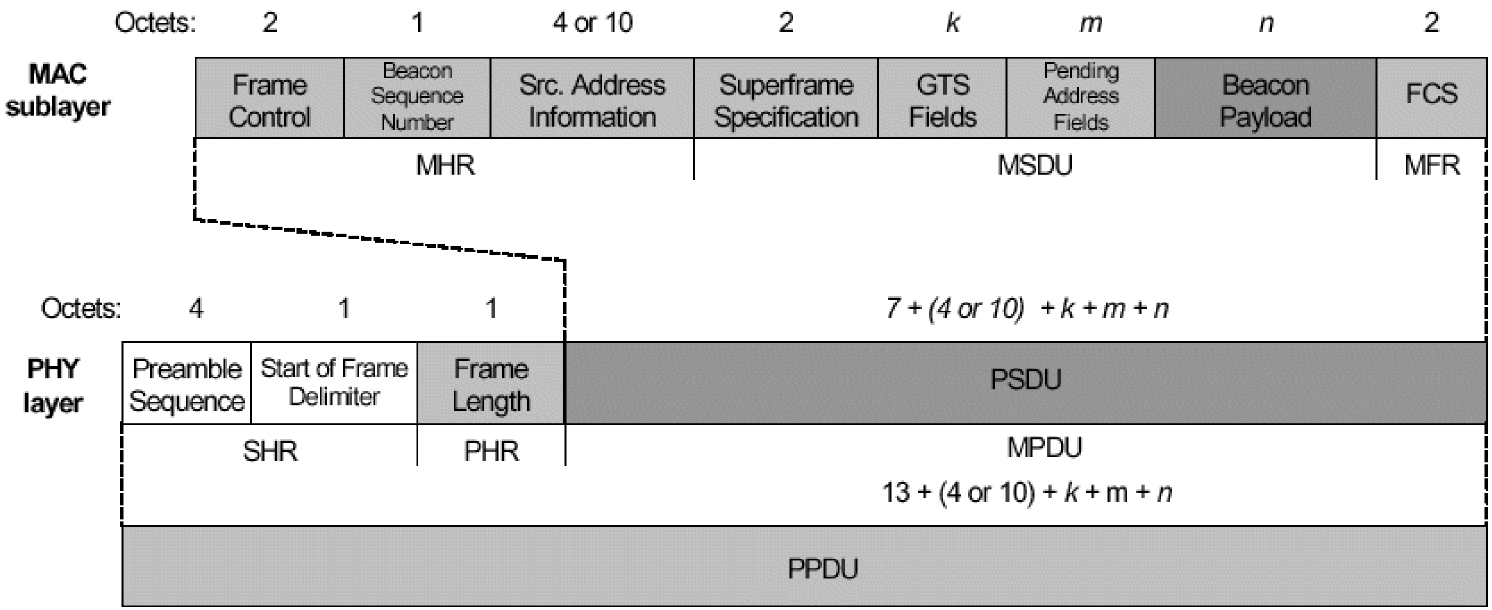
MAC Command Frame Format



- Mechanism for remote control/configuration of client nodes
- Allows a centralized network manager to configure individual clients no matter how large the network

IEEE 802.15.4 MAC Overview

Beacon Frame Format



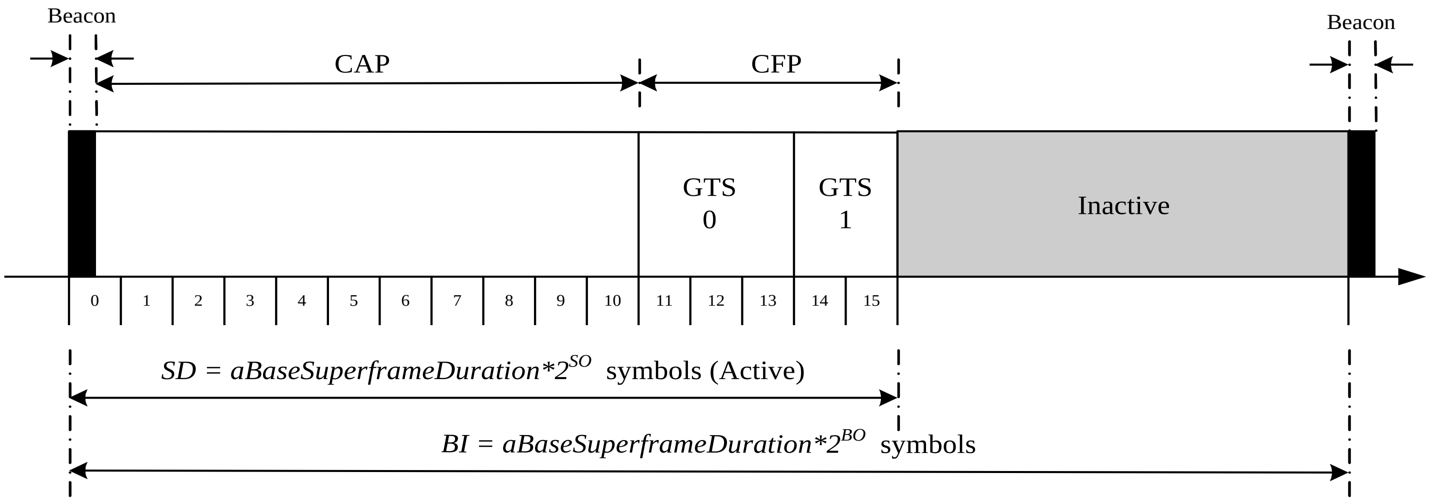
- Beacons add a new level of functionality to a network
- Client devices can wake up only when a beacon is to be broadcast, listen for their address, and if not heard, return to sleep
- Beacons are important for mesh and cluster tree networks to keep all of the nodes synchronized without requiring nodes to consume precious battery energy listening for long periods of time

IEEE 802.15.4 MAC Overview

- **Traffic Types**
  - Periodic data
    - Application determines Tx period (e.g. sensing data)
  - Intermittent data
    - Determined by applications or external interactions (e.g. switch of lighting)
  - Repetitive low latency data
    - Time slot allocation (e.g. mouse)

IEEE 802.15.4 MAC Overview

- **Superframe**
  - A superframe is divided into two parts
    - Inactive: all station sleep
    - Active:
      - Active period will be divided into 16 slots
      - 16 slots can further divided into two parts
        - Contention access period
        - Contention free period



IEEE 802.15.4 MAC Overview

- **Superframe**
  - Beacons are used for
    - starting superframes
    - synchronizing with other devices
    - announcing the existence of a PAN
    - informing pending data in coordinators
  - In a "beacon-enabled" network,
    - Devices use the slotted CAMA/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

IEEE 802.15.4 MAC Overview

- The structure of superframes is controlled by two parameters:
  - beacon order (BO) : decides the length of a superframe
  - superframe order (SO) : decides the length of the active potion in a superframe

- For a beacon-enabled network, the setting of BO and SO should satisfy the relationship $0 \leqq SO \leqq BO \leqq 14$

- For channels 11 to 26, the length of a superframe can range from 15.36 msec to 215.7 sec (= 3.5 min).

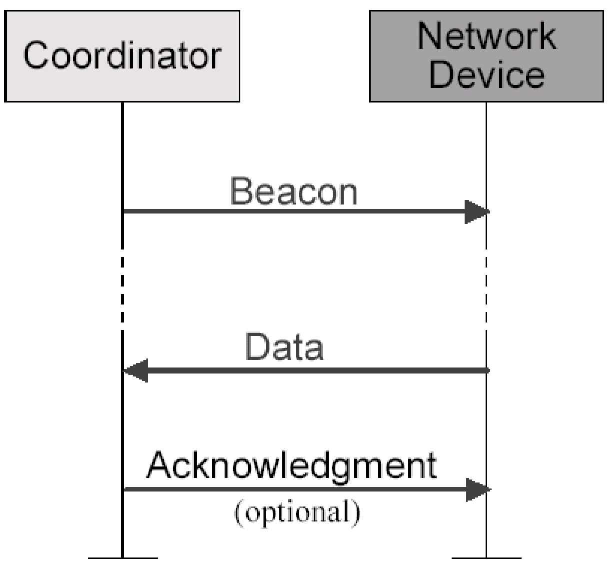
IEEE 802.15.4 MAC Overview

- Each device will be active for $2^{-(BO-SO)}$ portion of the time, and sleep for $1-2^{-(BO-SO)}$ portion of the time
- Duty Cycle:

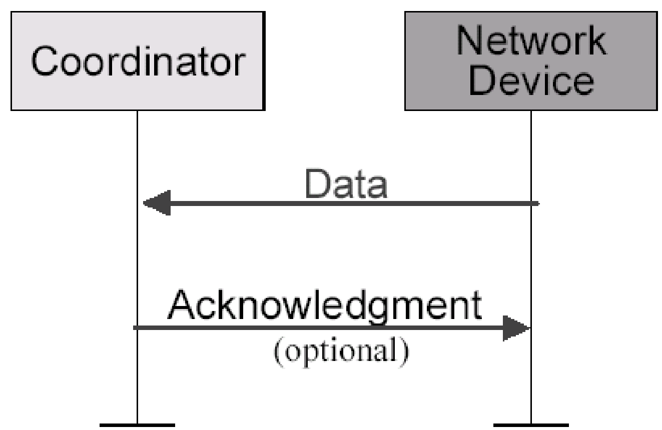
BO-SO	0	1	2	3	4	5	6	7	8	9	≧10
Duty cycle (%)	100	50	25	12	6.25	3.125	1.56	0.78	0.39	0.195	< 0.1

IEEE 802.15.4 MAC Overview

- **Data Transfer Model (I)**
  - Data transferred from device to coordinator
    - In a beacon-enable network, a device finds the beacon to synchronize to the superframe structure. Then it uses slotted CSMA/CA to transmit its data.
    - In a non-beacon-enable network, device simply transmits its data using unslotted CSMA/CA



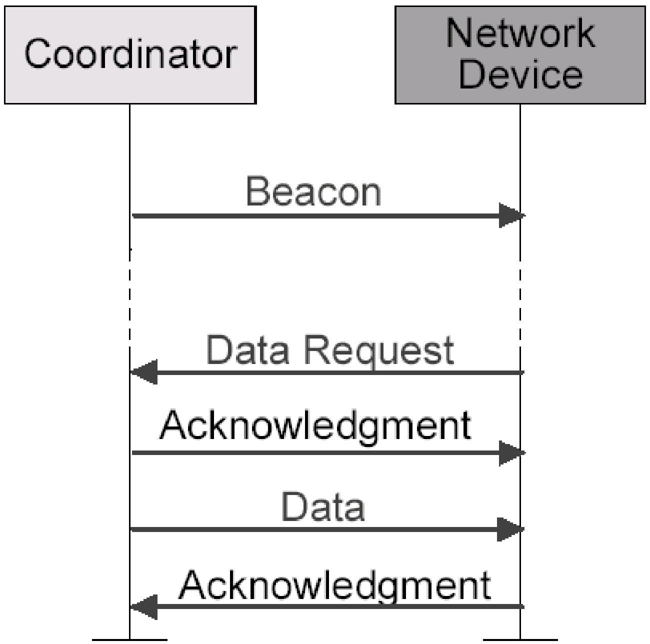
Communication to a coordinator
In a beacon-enabled network



Communication to a coordinator
In a non beacon-enabled network

IEEE 802.15.4 MAC Overview

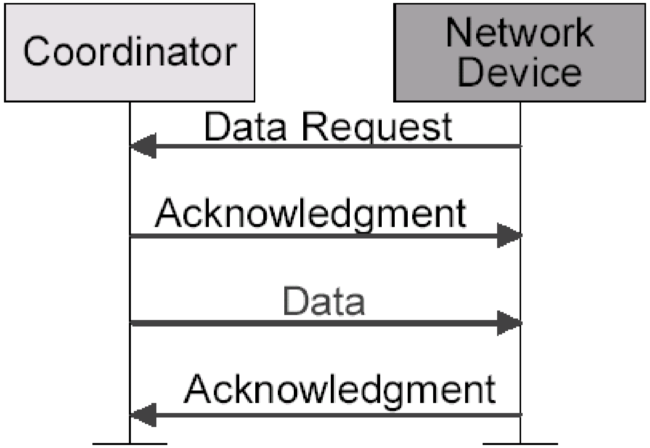
- **Data Transfer Model (II-1)**
  - Data transferred from coordinator to device in a beacon-enabled network:
    - The coordinator indicates in the beacon that some data is pending
    - A device periodically listens to the beacon and transmits a Data Requst command using slotted CSMA/CA.
    - Then ACK, Data, and ACK follow …



Communication from a coordinator
In a beacon-enabled network

IEEE 802.15.4 MAC Overview

- Data transferred from coordinator to device in a non-beacon-enable network:
  - The device transmits a Data Request using unslotted CSMA/CA
  - If the coordinator has its pending data, an ACK is replied.
  - Then the coordinator transmits Data using unslotted CSMA/CA
  - If there is no pending data, a data frame with zero length payload is transmitted.



Communication from a coordinator in a non beacon-enabled network

IEEE 802.15.4 MAC Overview

- **Channel Access Mechanism**
  - Two type channel access mechanism:
    - beacon-enabled networks → slotted CSMA/CA channel access mechanism
    - non-beacon-enabled networks → unslotted CSMA/CA channel access mechanism

IEEE 802.15.4 MAC Overview

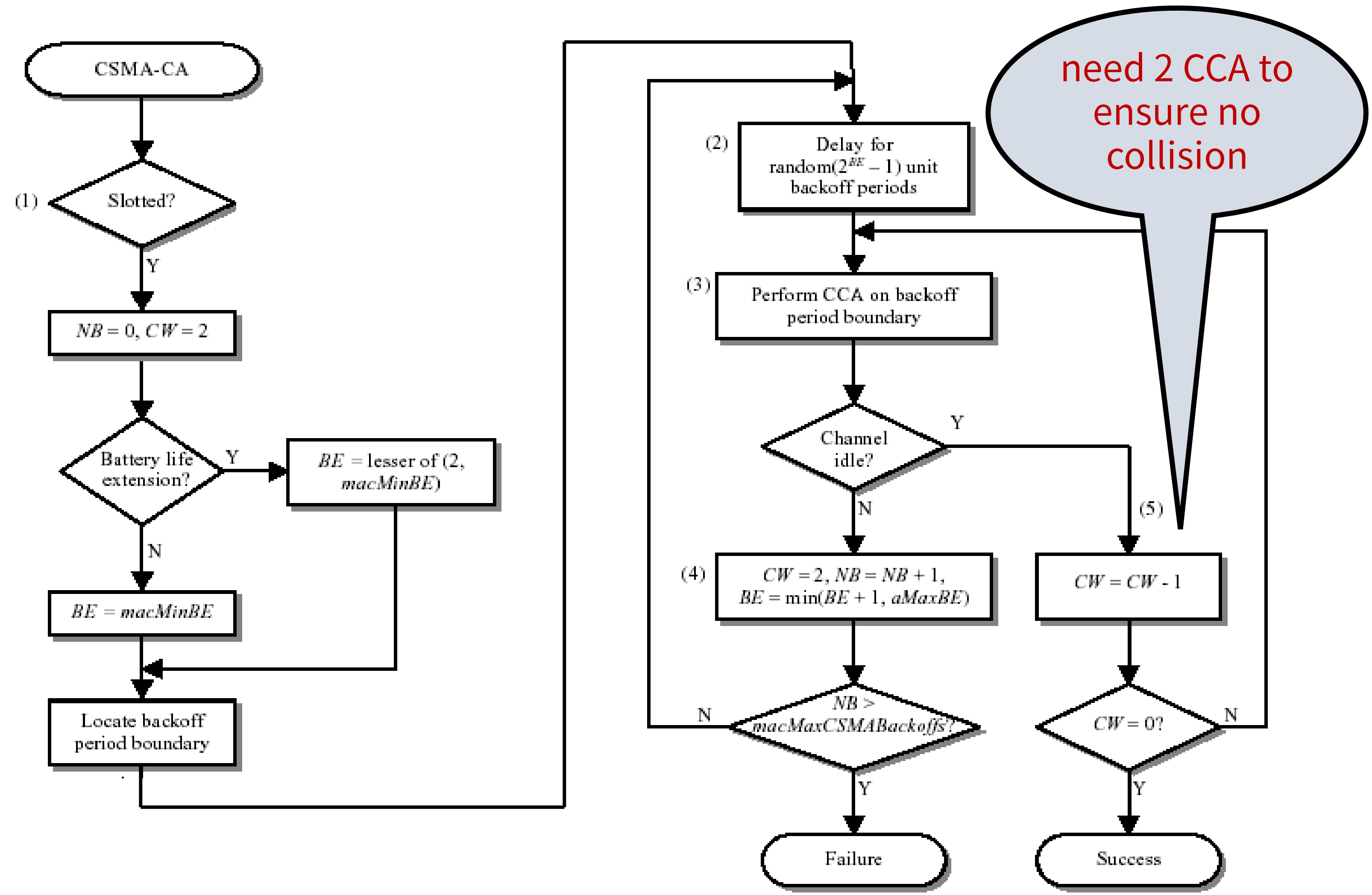
- **Slotted CSMA/CA algorithm**
  - The backoff period boundaries of every device in the PAN shall be aligned with the superframe slot boundaries of the PAN coordinator
    - i.e. the start of first backoff period of each device is aligned with the start of the beacon transmission
  - The MAC sublayer shall ensure that the PHY layer commences all of its transmissions on the boundary of a backoff period

IEEE 802.15.4 MAC Overview

- Each device maintains 3 variables for each transmission attempt
  - NB: number of times that backoff has been taken in this attempt (if exceeding macMaxCSMABackoff, the attempt fails)
  - BE: the backoff exponent which is determined by NB
  - CW: contention window length, the number of clear slots that must be seen after each backoff
    - always set to 2 and count down to 0 if the channel is sensed to be clear
    - The design is for some PHY parameters, which require 2 CCA for efficient channel usage.

- Battery Life Extension:
  - designed for very low-power operation, where a node only contends in the first 6 slots

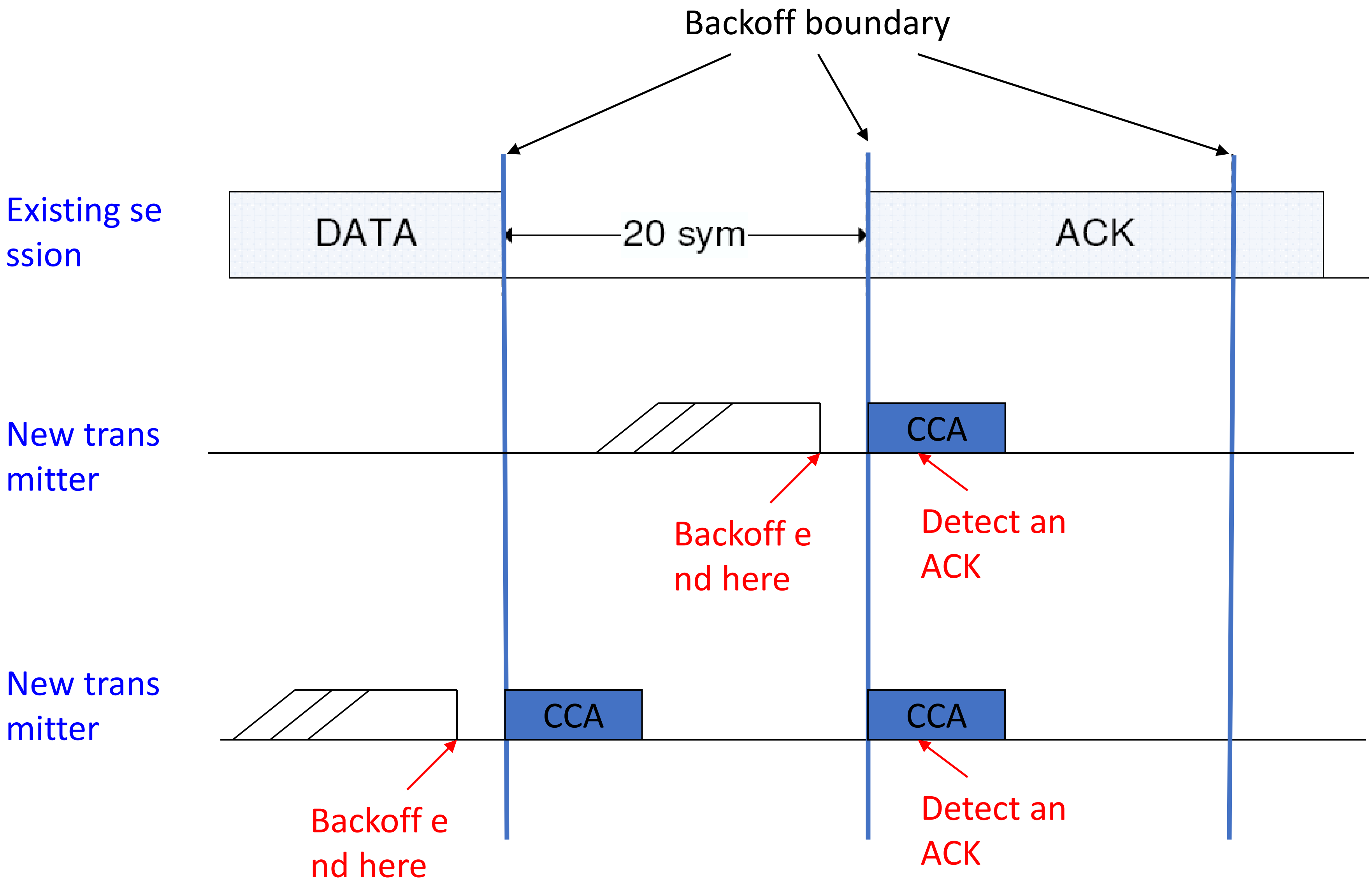
IEEE 802.15.4 MAC Overview



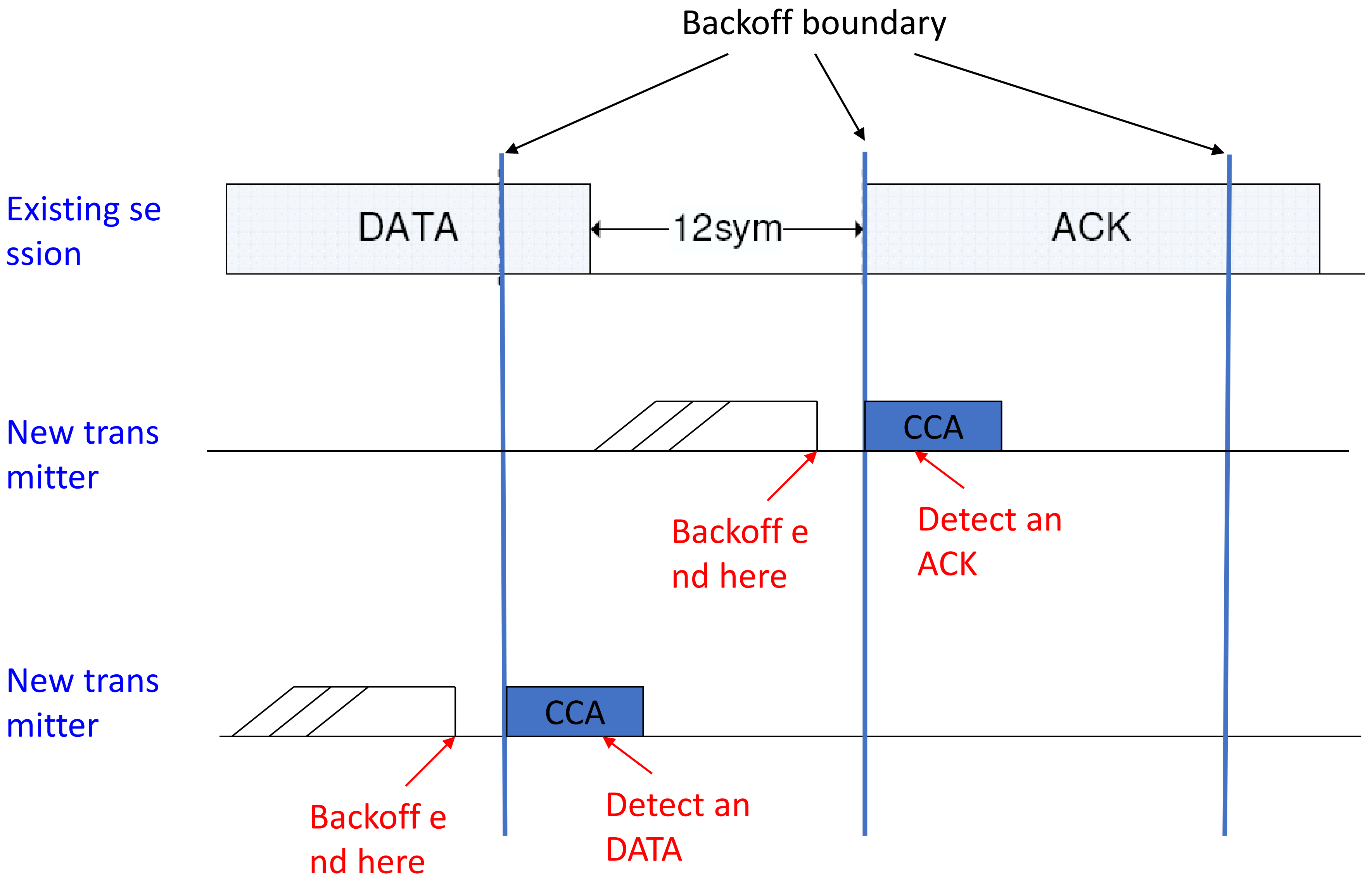
IEEE 802.15.4 MAC Overview

- **Why 2 CCAs to Ensure Collision-Free**
  - Each CCA occurs at the boundary of a backoff slot (= 20 symbols), and each CCA time = 8 symbols.
  - The standard species that a transmitter node performs the CCA twice in order to protect acknowledgment (ACK).
    - When an ACK packet is expected, the receiver shall send it after a t_{ACK} time on the backoff boundary
      - t_{ACK} varies from 12 to 31 symbols
    - One-time CCA of a transmitter may potentially cause a collision between a newly-transmitted packet and an ACK packet.
    - (See examples below)

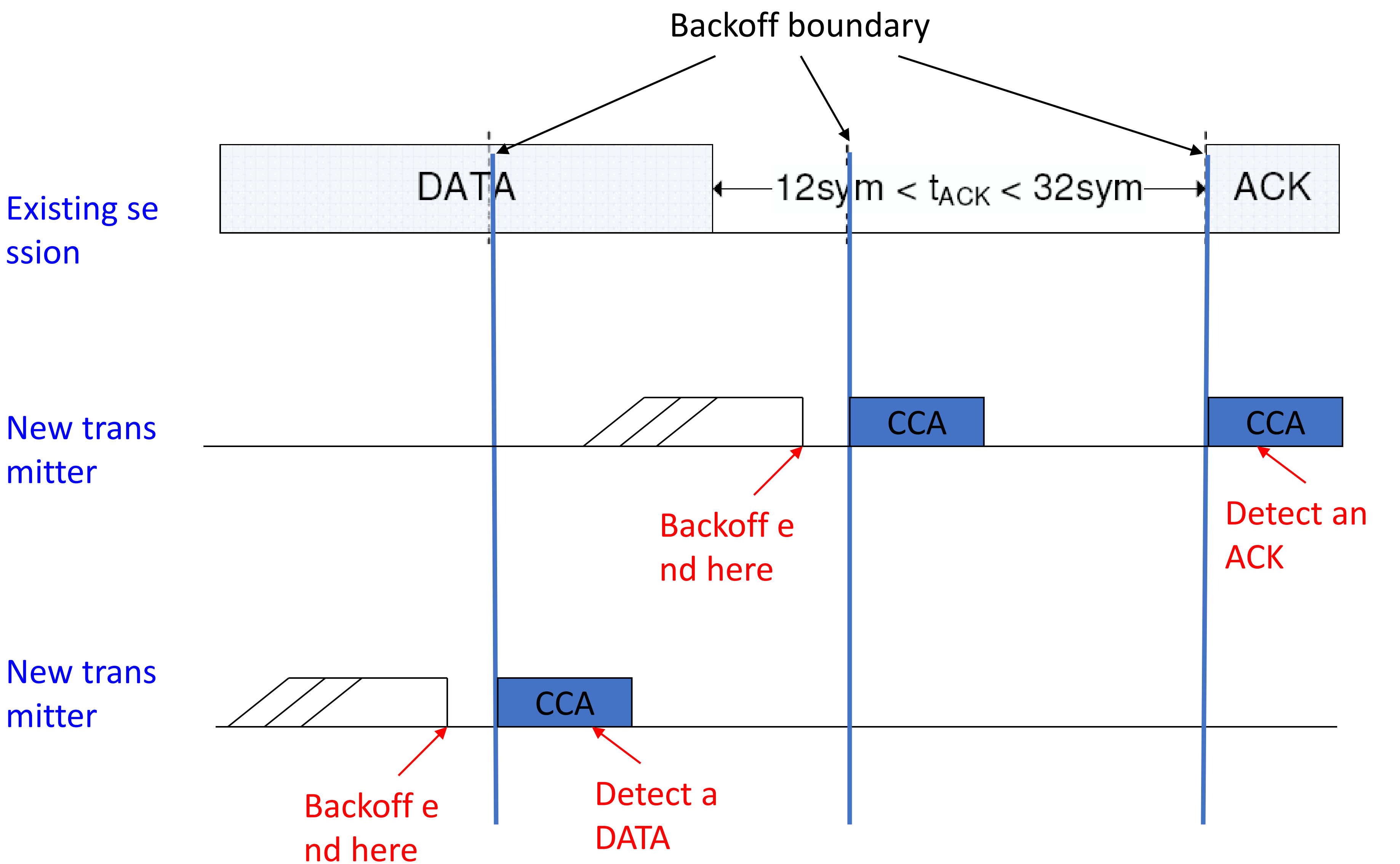
Why 2 CCAs (case 1)



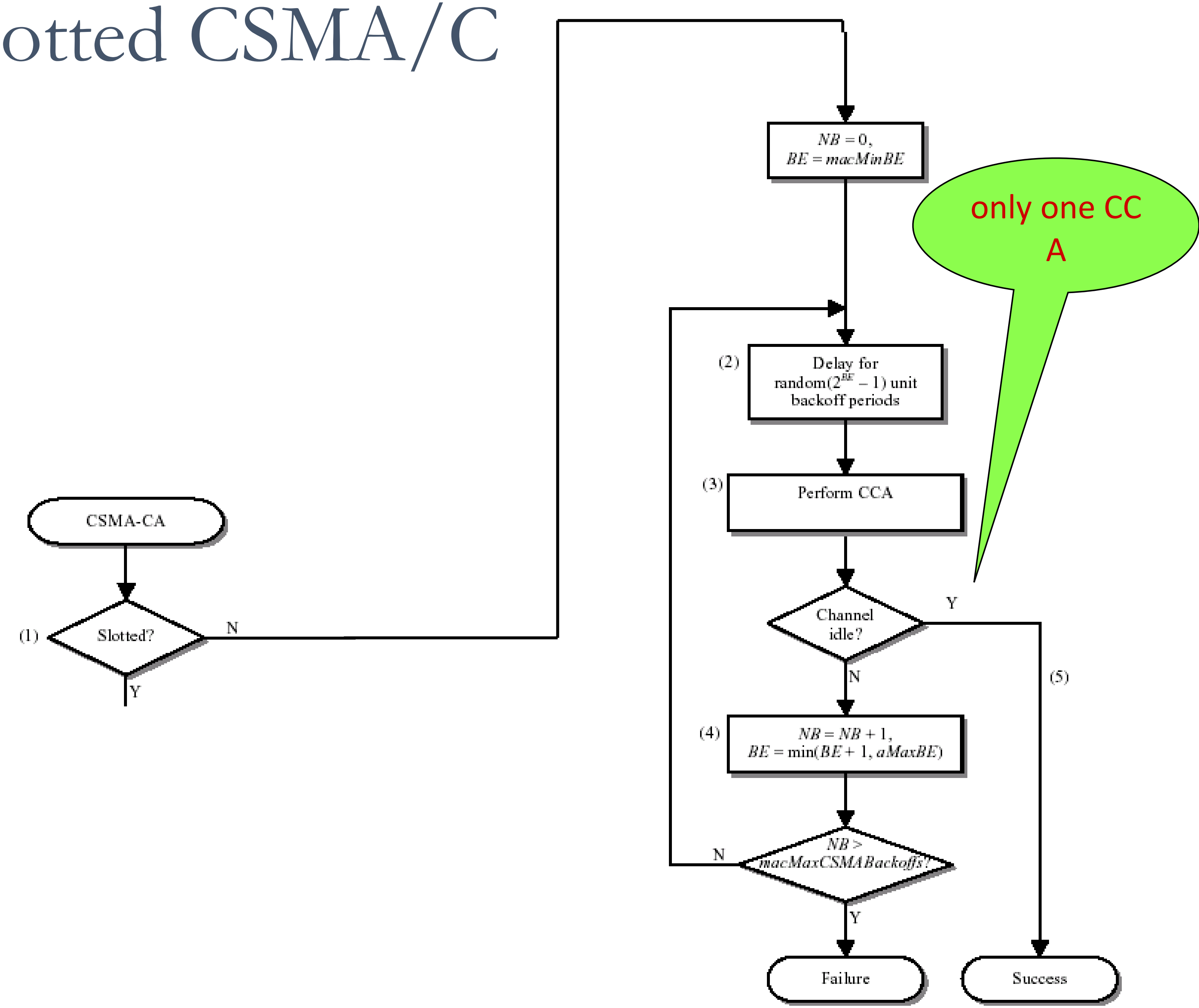
Why 2 CCAs (Case 2)



Why 2 CCAs (Case 3)



Unslotted CSMA/CA



GTS Concepts (I)

- A **guaranteed time slot (GTS)** allows a device to operate on the channel within a portion of the superframe
- A GTS shall only be allocated by the PAN coordinator
- The PAN coordinator can allocated up to **7 GTSs** at the same time
- The PAN coordinator decides whether to allocate GTS based on:
  - Requirements of the GTS request
  - The current available capacity in the superframe

GTS Concepts (II)

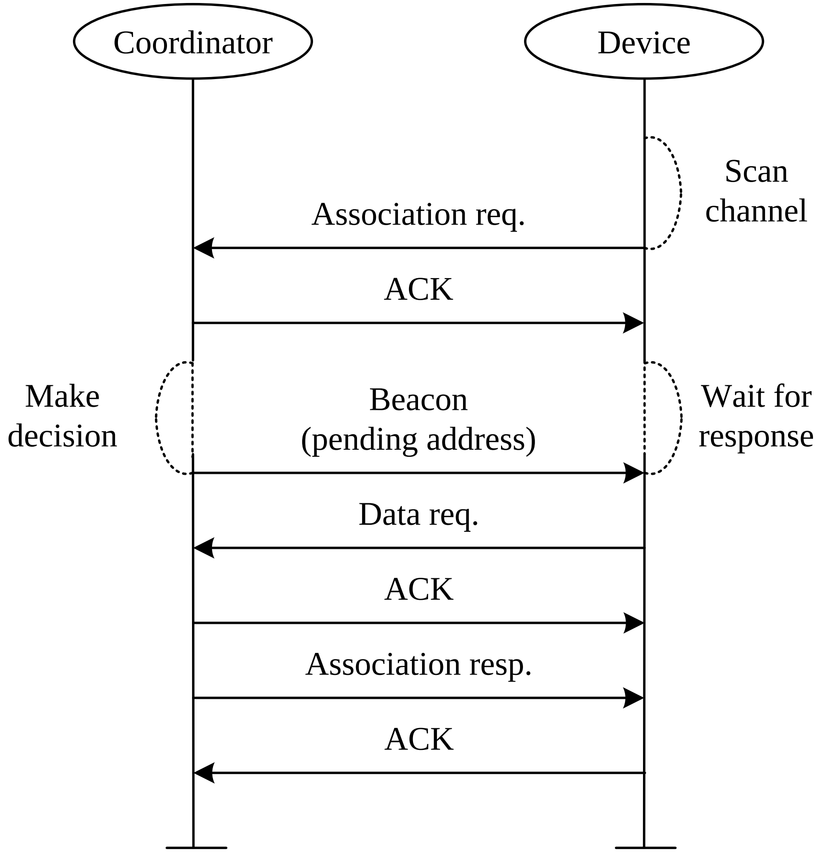
- **A GTS can be deallocated**
  - At any time at the discretion of the PAN coordinator or
  - By the device that originally requested the GTS
- **A device that has been allocated a GTS may also operate in the CAP**
- **A data frame transmitted in an allocated GTS shall use only short addressing**

GTS Concepts (III)

- **Before GTS starts, the GTS direction shall be specified as either transmit or receive**
  - Each device may request one transmit GTS and/or one receive GTS
- **A device shall only attempt to allocate and use a GTS if it is currently tracking the beacon**
- **If a device loses synchronization with the PAN coordinator, all its GTS allocations shall be lost**
- **The use of GTSs be an RFD is optional**

Association Procedures (1/2)

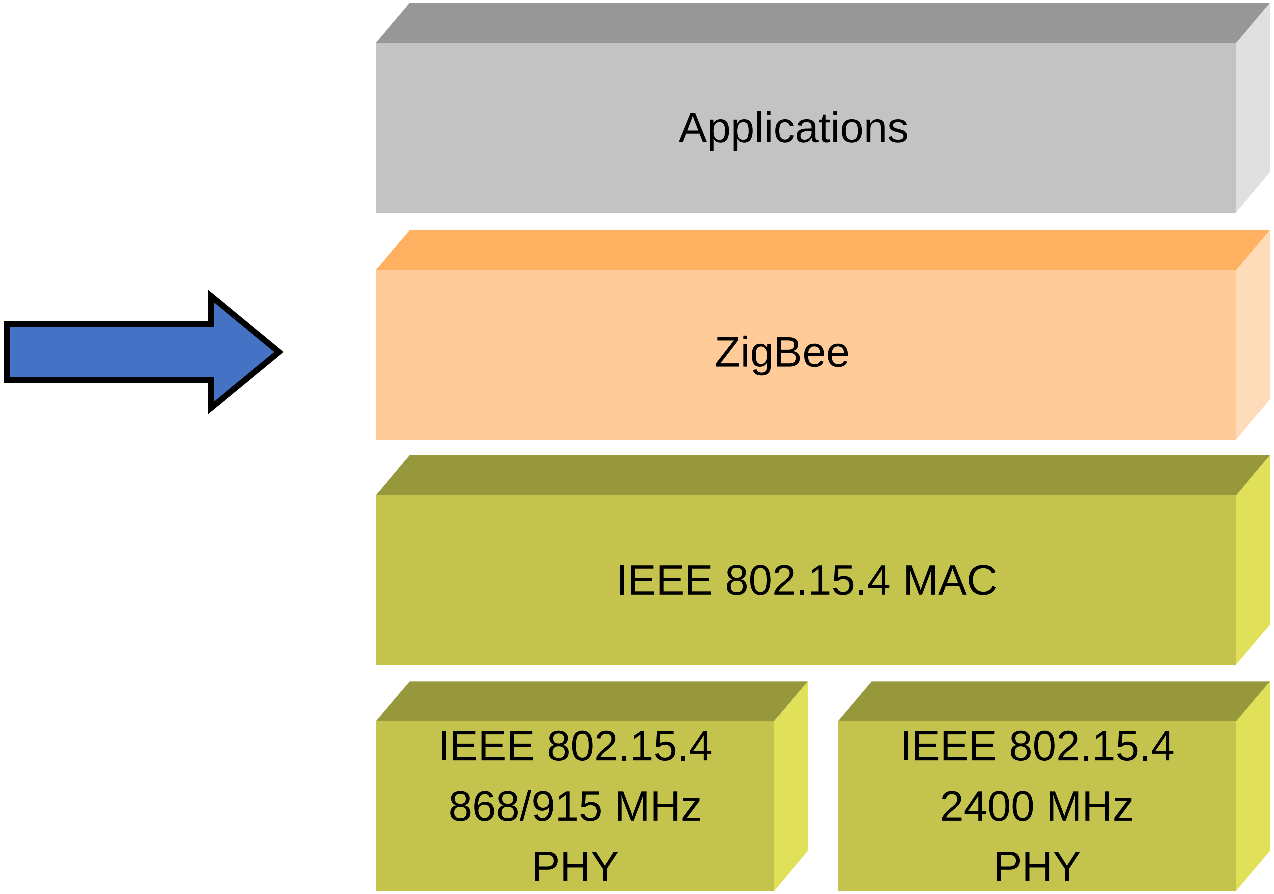
- A device becomes a member of a PAN by associating with its coordinator
- Procedures



Association Procedures (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*.**

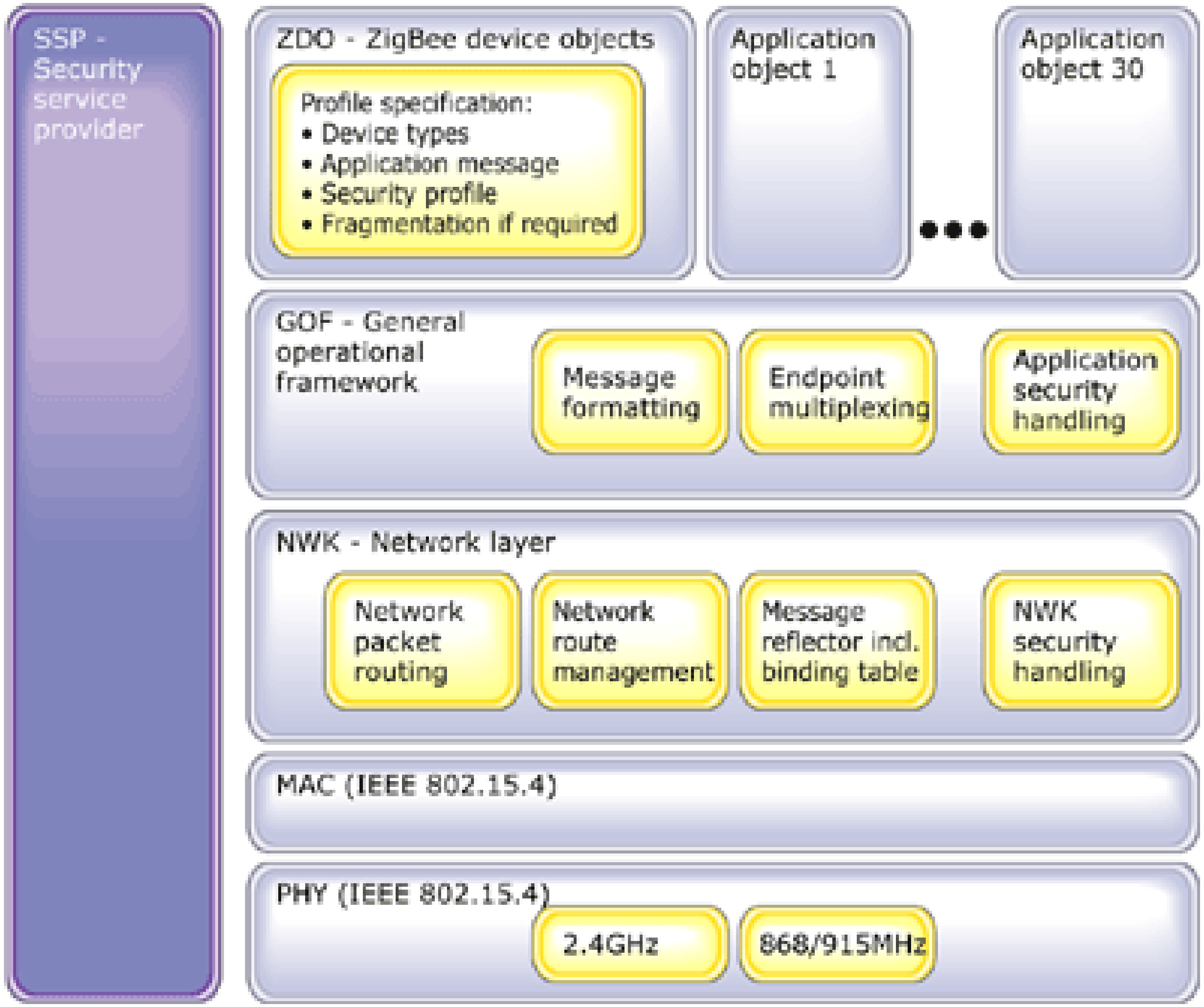
IEEE 802.15.4 Architecture



- **Network Routing**
- **Address translation**
- **Packet Segmentation**
- **Profiles**

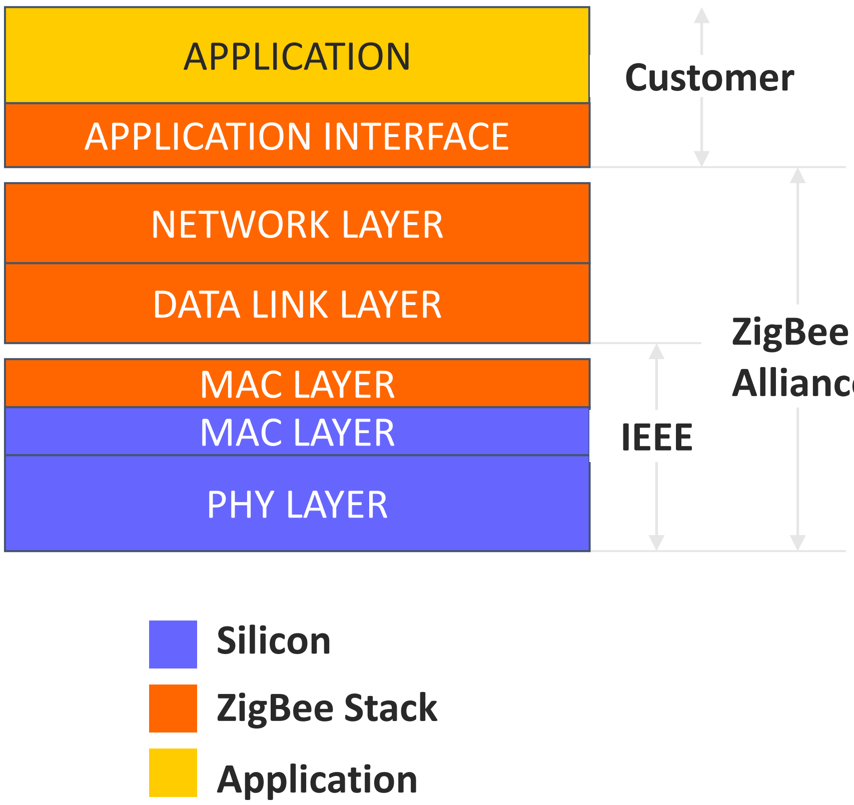
Zigbee Overview

- **ZigBee Stack Architecture**



Zigbee Overview

- **Protocol Stack Features**
  - 8-bit microcontroller
  - Full protocol stack <32 k
  - Simple node-only stack ~4k
  - Coordinators require extra RAM
    - Node device database
    - Transaction table
    - Pairing table



Zigbee Overview

Wireless Technology Comparison Chart

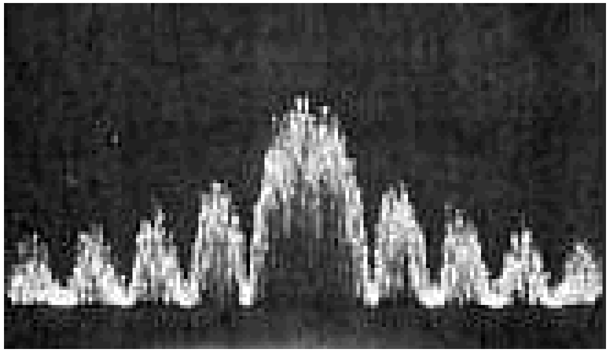
Standard	Bandwidth	Power Consumption	Protocol Stack Size	Stronghold	Applications
Wi-Fi	Up to 54Mbps	400+mA TX, standby 20mA	100+KB	High data rate	Internet browsing, PC networking, file transfers
Bluetooth	1Mbps	40mA TX, standby 0.2mA	~100+KB	Interoperability, cable replacement	Wireless USB, handset, headset
ZigBee	250kbps	30mA TX, standby 356 µA	34KB /14KB	Long battery life, low cost	Remote control, battery-operated products, sensors

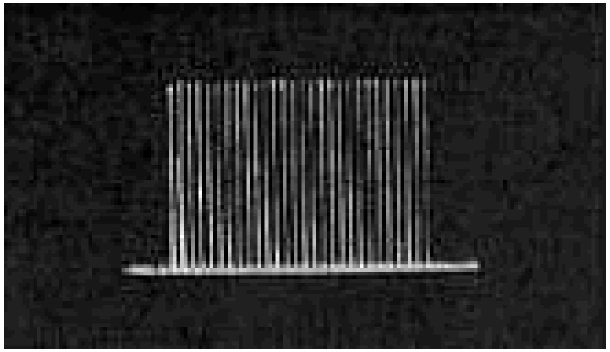
Zigbee vs. Bluetooth

Bluetooth is Best	But ZigBee is Better
• Ad-hoc networks between capable devices • Handsfree audio • Screen graphics, pictures… • File transfer	• The Network is static • Lots of devices • Infrequently used • Small Data Packets

Zigbee vs. Bluetooth

- **Air Interface**
  - ZigBee
    - DSSS
    - 11 chips/ symbol
    - 62.5 K symbols/s
    - 4 Bits/ symbol
    - Peak Information Rate
      - ~128 Kbit/second
  - Bluetooth
    - FHSS
    - 1 M Symbol / second
    - Peak Information Rate
      - ~720 Kbit/second





Zigbee vs. Bluetooth

ZigBee:

- New slave enumeration = 30ms typically
- Sleeping slave changing to active = 15ms typically
- Active slave channel access time = 15ms typically

Bluetooth:

- New slave enumeration = >3s
- Sleeping slave changing to active = 3s typically
- Active slave channel access time = 2ms typically

ZigBee protocol is optimized for timing critical applications

Zigbee vs. Bluetooth

- **Power Considerations**
  - ZigBee
    - 2+ years from ‘normal’ batteries
    - Designed to optimise slave power requirements
  - Bluetooth
    - Power model as a mobile phone (regular charging)
    - Designed to maximise ad-hoc functionality

Zigbee Overview

ZigBee Products

Control4 Home Automation System
http://www.control4.com/products/components/complete.htm

Eaton Home HeartBeat monitoring system
www.homeheartbeat.com

Software, Development Kits
- AirBee, http://www.airbeewireless.com/products.php
- Software Technologies Group, http://www.stg.com/wireless/

Chip Sets
- Ember, http://www.ember.com/index.html
- ChipCon, http://www.chipcon.com
- Freescale, http://www.freescale.com