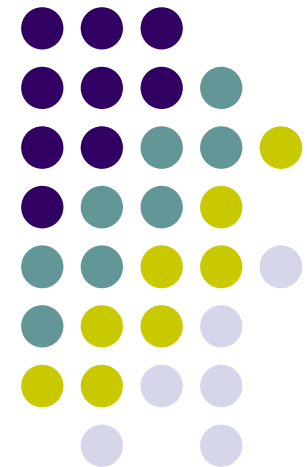# IEEE 802.15.4

Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)

Speaker :   Chun-Yi Chen

Advisor :   Ren-Guey Lee

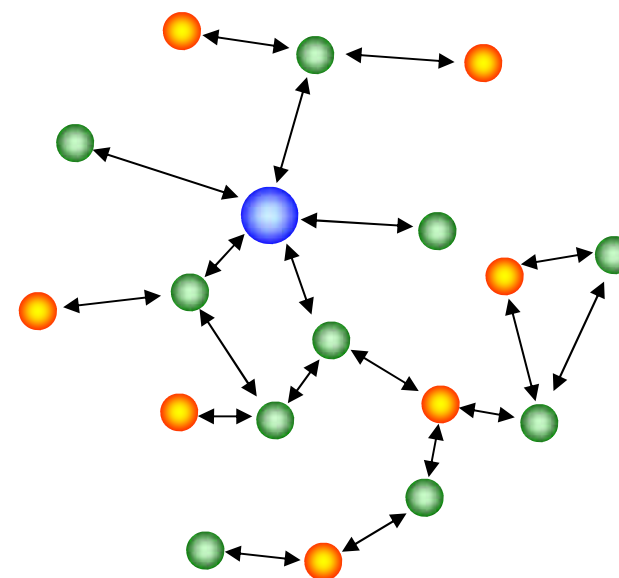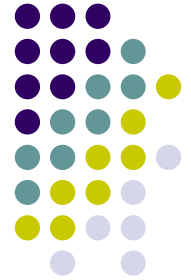Date   :   2007/09/07

Outline

- Introduction
- IEEE 802.15.4 PHY
- IEEE 802.15.4 MAC
  - Overview
  - Topologies
  - Superframe Structure
  - Frame Formatting
  - Data and Management Service
  - Interframe Spacing
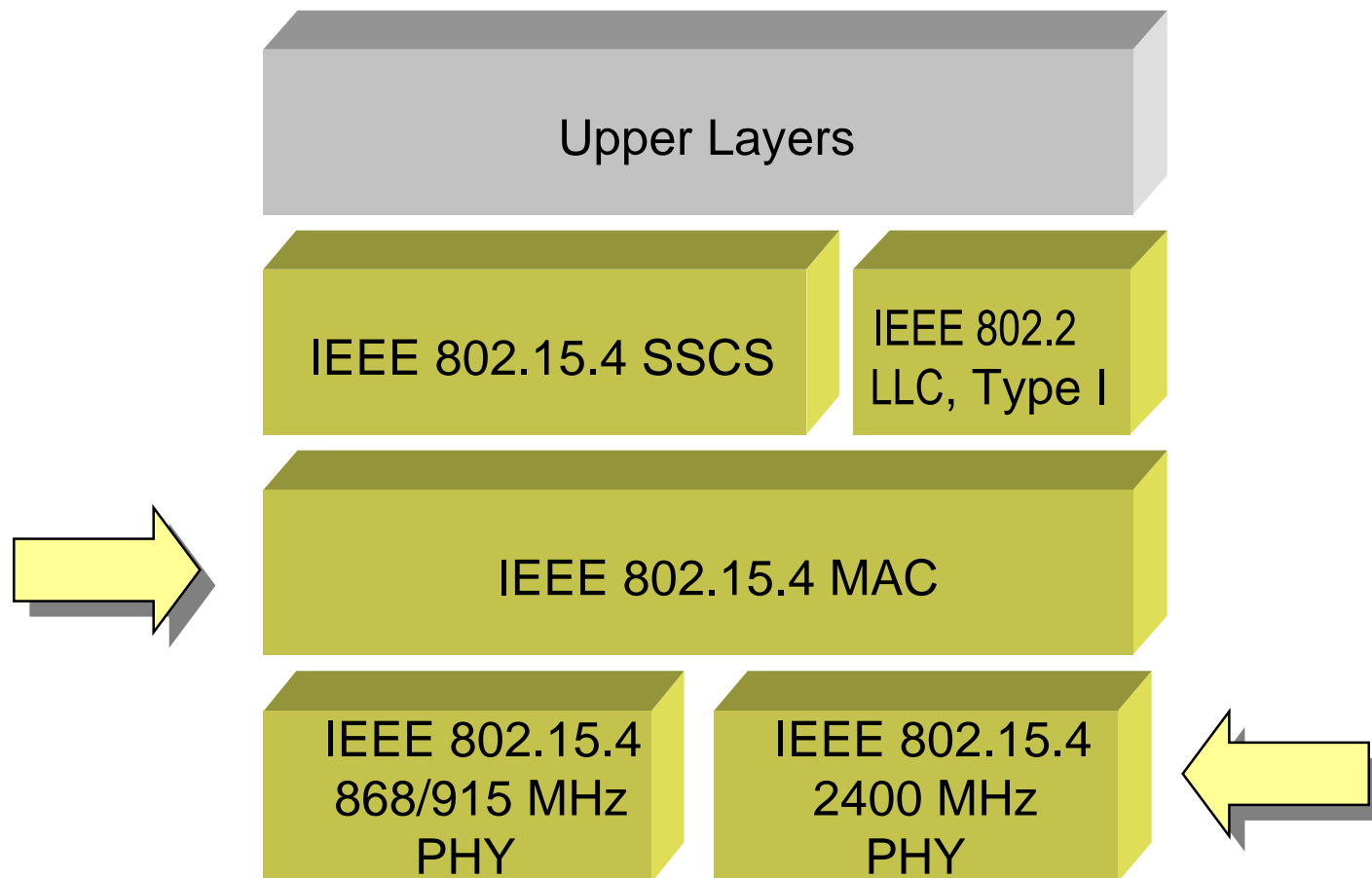 - CSMA-CA Procedure
- References

Introduction 1

- Characteristics of LR-WPAN :
    - Over-the-air data rates of **250 kb/s, 100kb/s, 40 kb/s, and 20 kb/s**
    - **Star** or **peer-to-peer** operation
    - Allocated 16-bit short or 64-bit extended addresses
    - Optional allocation of guaranteed time slots (**GTSs**)
    - Carrier sense multiple access with collision avoidance (**CSMA-CA**) channel access
    - Fully acknowledged protocol for transfer reliability
    - Low power consumption
    - Energy detection (ED)
    - Link quality indication (LQI)
    - 16 channels in the 2450 MHz band, 30 channels in the 915 MHz band, and 3 channels in the 868 MHz band

Introduction 2

- **IEEE 802.15.4 Architecture**

Upper Layers

IEEE 802.15.4 SSCS

IEEE 802.2 LLC, Type I

IEEE 802.15.4 MAC

IEEE 802.15.4 868/915 MHz PHY

IEEE 802.15.4 2400 MHz PHY

IEEE 802.15.4 PHY [1]

- **Operating Frequency Bands**

868MHz/ 915MHz PHY

Channel 0

868.3 MHz

Channels 1-10

2 MHz

902 MHz   928 MHz

2.4 GHz PHY

Channels 11-26

5 MHz

2.4 GHz

2.4835 GHz
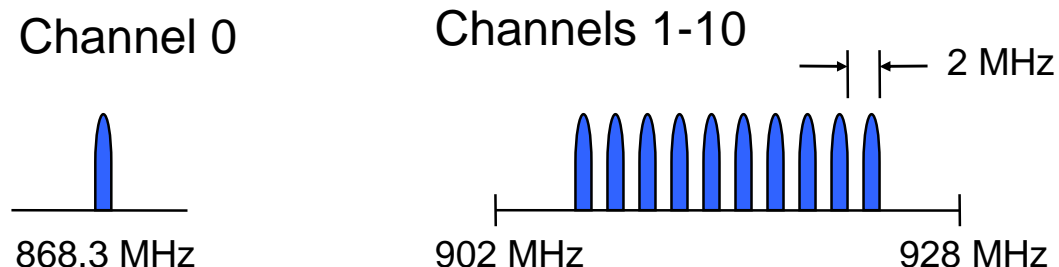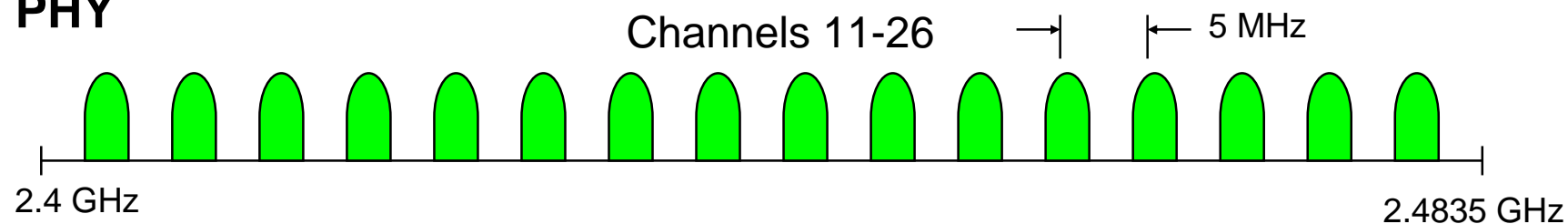
IEEE 802.15.4 PHY [2]

- **Co-exists with WiFi, Bluetooth**

Note: Channels 25, 26 are non-overlapping

802.15.4: Ch. 11 to Ch. 26

Ch. 15   Ch. 20   5 MHz Spacing   Ch. 25 Ch. 26

2405 MHz   2 MHz   2480 MHz

802.11: Ch. 1 to Ch. 11

Ch. 1   25 MHz Spacing   Ch. 6   Ch. 11

22 MHz

2412 MHz   2425 MHz   2437 MHz   2450 MHz   2462 MHz   2475 MHz
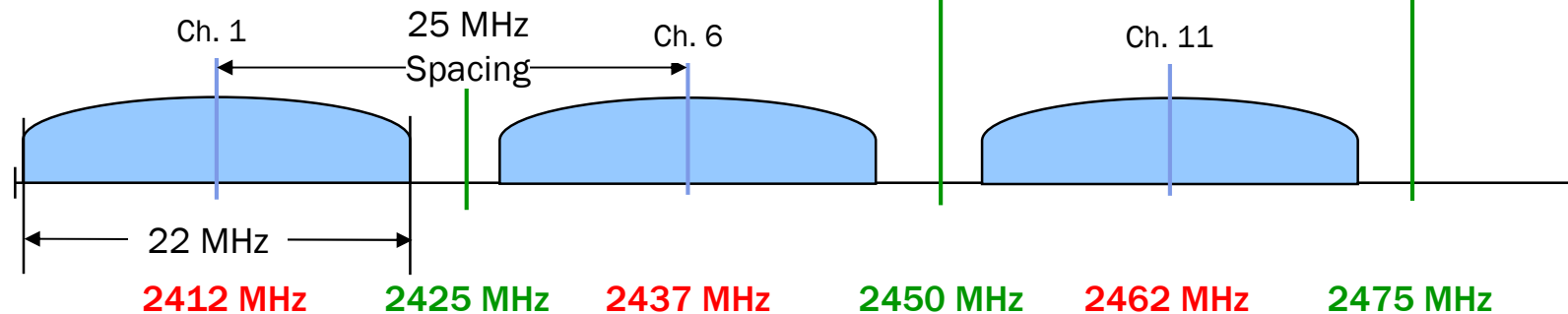
IEEE 802.15.4 PHY ₃

- **Packet Structure**

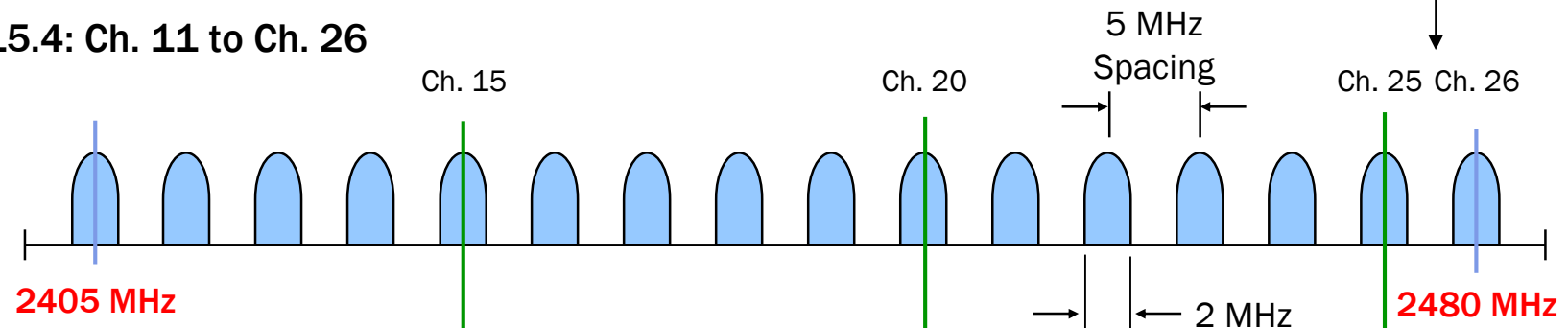   **PHY Packet Fields**
    - Preamble (32 bits) – Symbol synchronization
    - Start of Packet Delimiter (8 bits) – Frame synchronization
    - PHY Header (8 bits) – Specifies PSDU length
    - PSDU (up to 127 bytes) – Data field

Preamble Sequence	Start of Packet Delimiter	PHY Header	PHY Service Data Unit (PSDU)

6 Bytes — ≤ 127 Bytes

(0.2 ms @ 250 kbps)
(1.2 ms @ 40 kbps)

(< 4.1 ms @ 250 kbps)
(< 50.8 ms @ 40 kbps)
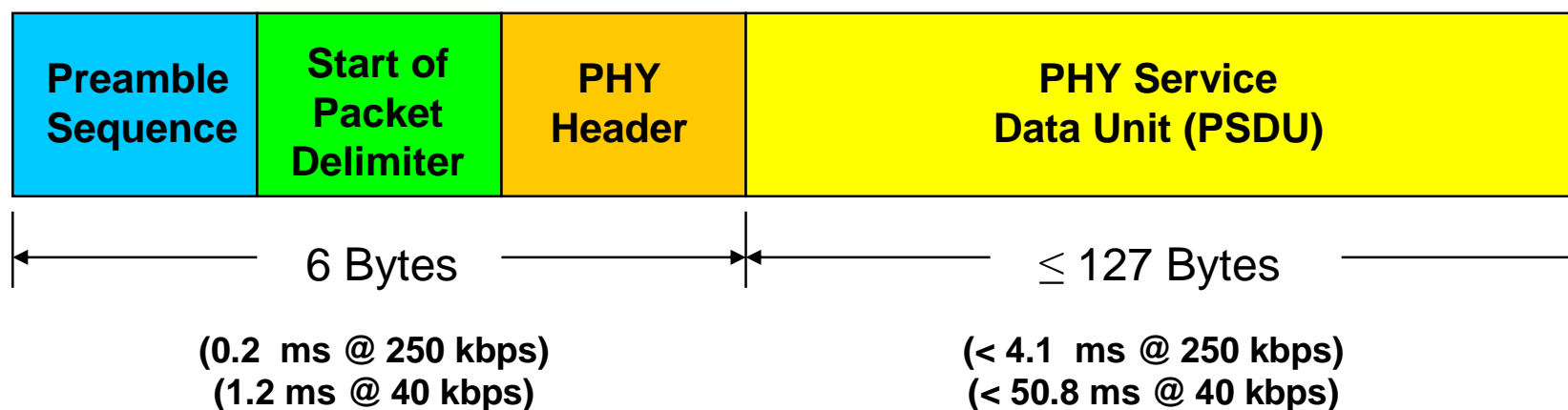
IEEE 802.15.4 PHY [4]

- **Modulation/Spreading**

  2.4 GHz PHY
  - Data rate is **250 kbps** (4 bits/symbol, 62.5 ksymbols/s)
  - Data modulation is **16-ary orthogonal modulation**
  - 16 symbols are orthogonal set of 32-chip PN codes
  - Chip modulation is **O-QPSK** with half-sine pulse shape
  - Chip rate is 2.0 Mchip/s

  868MHz/915MHz PHY
  - Data rate is **20 kbps @ 868 MHz, 40 kbps @ 915 MHz**
  - Data modulation is **BPSK** with differential encoding
  - Spreading code is a 15-chip m-sequence
  - Chip modulation is **BPSK** with raised-cosine pulse shape ($\alpha=1.0$)
  - Chip rate is 0.3 Mchip/s at 868 MHz, 0.6 Mchip/s at 915 MHz

IEEE 802.15.4 MAC
Overview 1

- Star and peer-to-peer topologies

- Optional frame structure

- Association

- CSMA-CA channel access mechanism

- Packet validation and message rejection

- Optional guaranteed time slots

- Guaranteed packet delivery

- Facilitates low-power operation

IEEE 802.15.4 MAC
Overview 2

- **Full Function Device** (FFD)
  - Any topology
  - PAN coordinator capable
  - Talks to any other device
  - Implements complete protocol set

- **Reduced Function Device** (RFD)
  - Limited to star topology or end-device in a peer-to-peer network.
  - Cannot become a PAN coordinator
  - Very simple implementation
  - Reduced protocol set

IEEE 802.15.4 MAC
Overview 3

- **Network Device:**

  - An RFD or FFD implementation containing an IEEE 802.15.4 medium access control and physical interface to the wireless medium.

- **Coordinator:**

  - An FFD with network device functionality that provides coordination and other services to the network.

- **PAN Coordinator:**

  - A coordinator that is the principal controller of the PAN. A network has exactly one PAN coordinator.

IEEE 802.15.4 MAC
Topologies 1

- **Star Topology**

PAN
coordinator

FFD

RFD

Master/slave

—— Communications flow
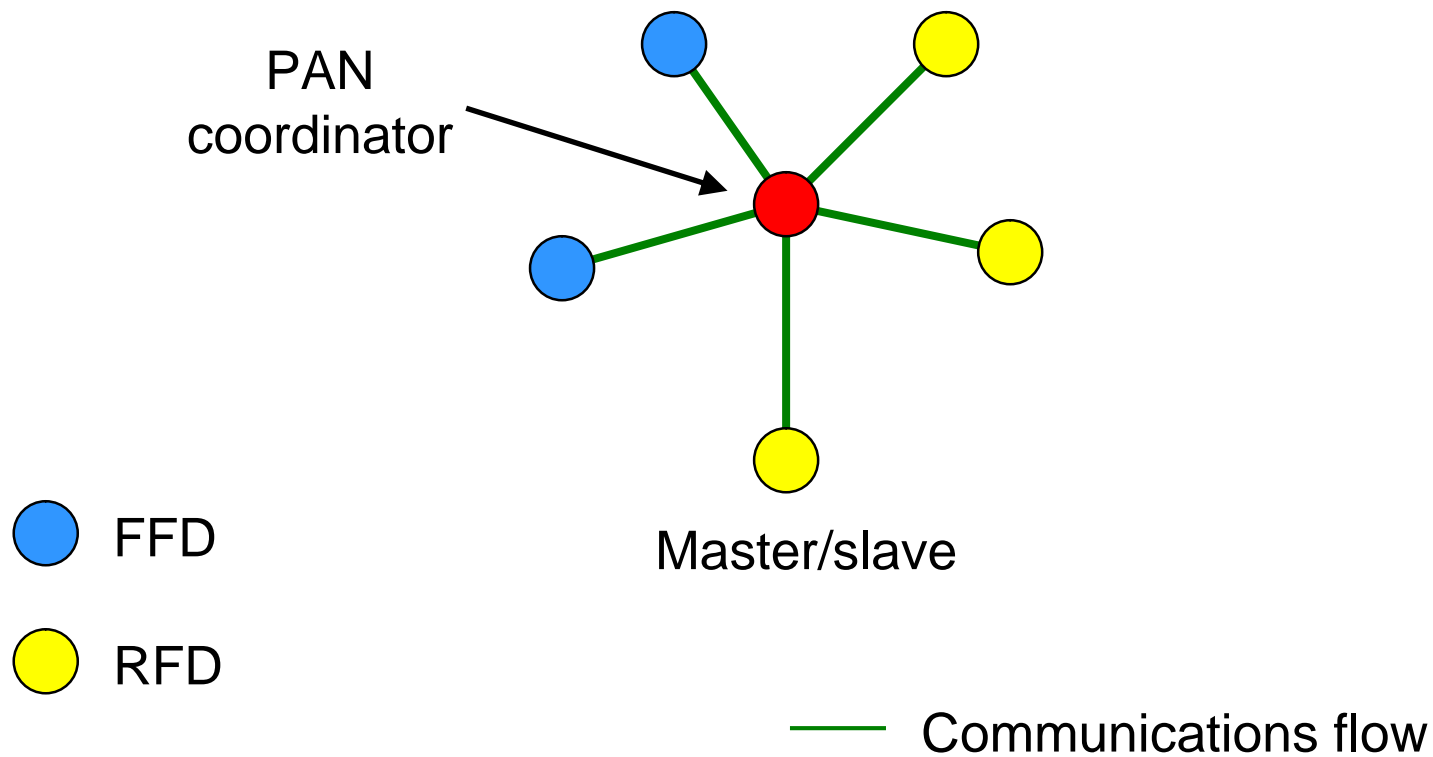
IEEE 802.15.4 MAC
Topologies 2

- **Peer-Peer Topology**

FFD

RFD

PAN coordinators

Point to point

Cluster tree

—— Communications flow
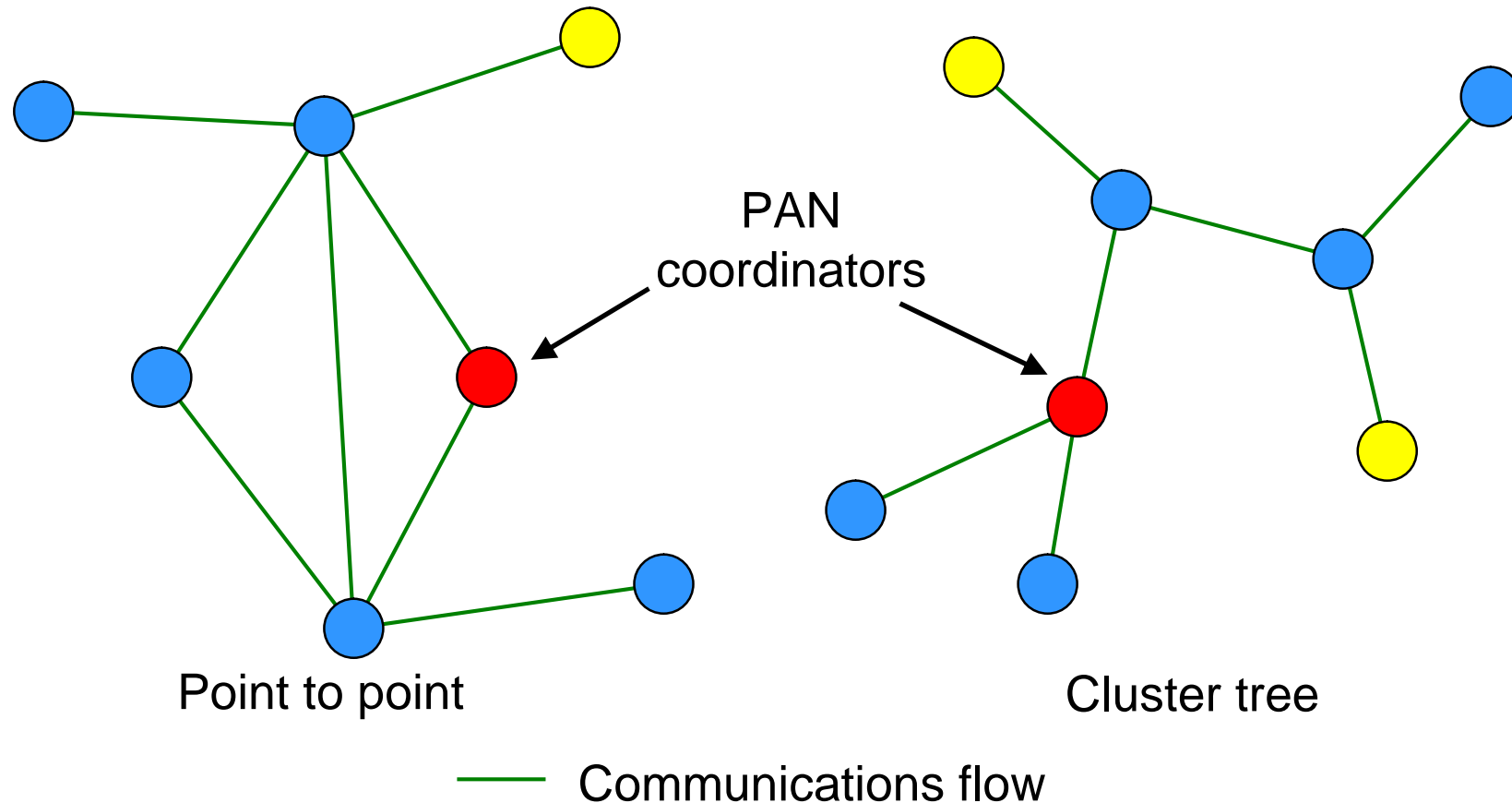
IEEE 802.15.4 MAC
Topologies 3

- **Combined Topology**

FFD

RFD

Communications flow

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

PAN coordinator

IEEE 802.15.4 MAC
Superframe Structure [1]

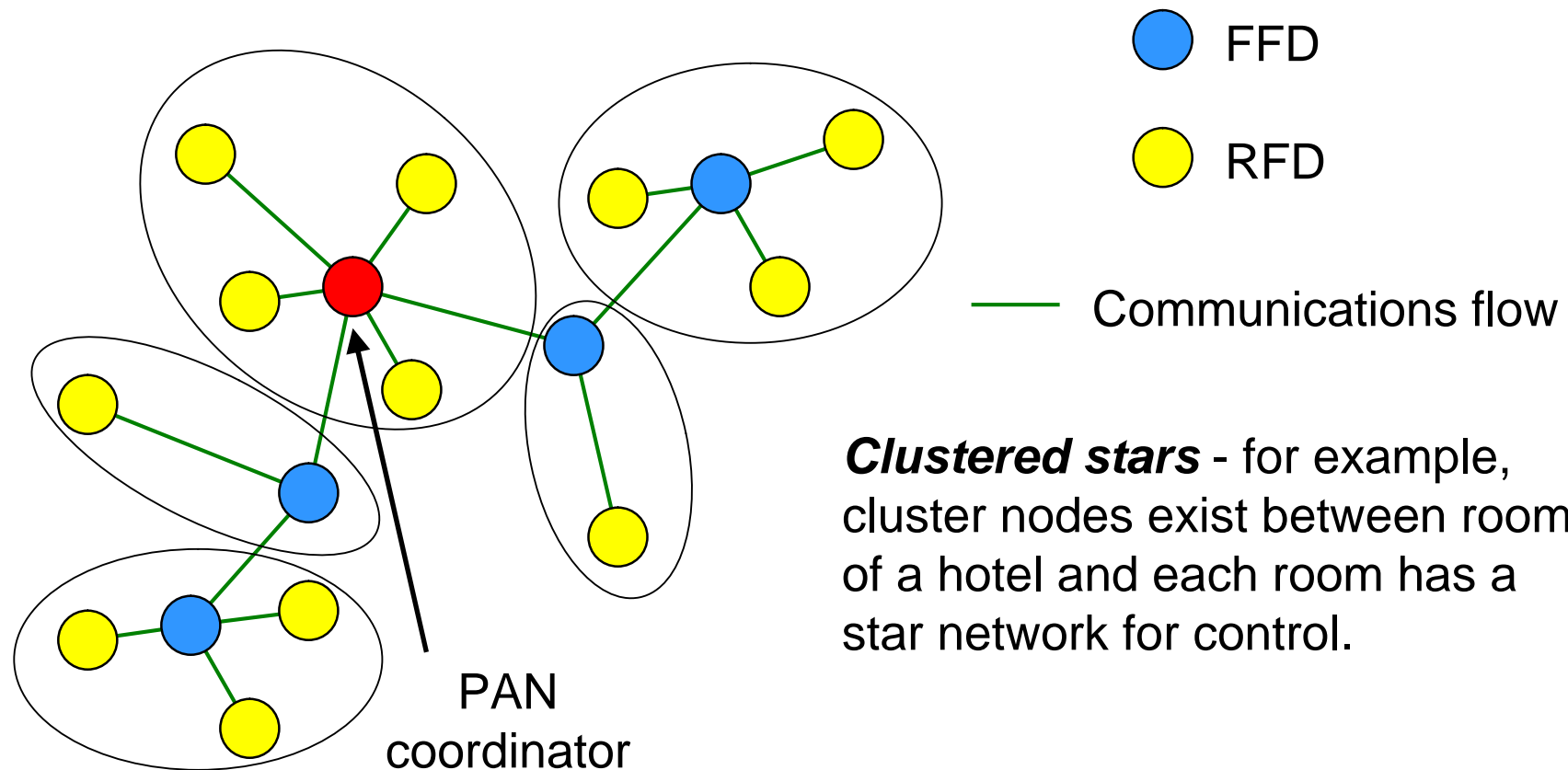Battery life extension

GTS 3 — GTS 2 — GTS 1

| Contention Access Period | Contention Free Period |

Slot: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

$15ms * 2^n$
where $0 \geq n \geq 14$
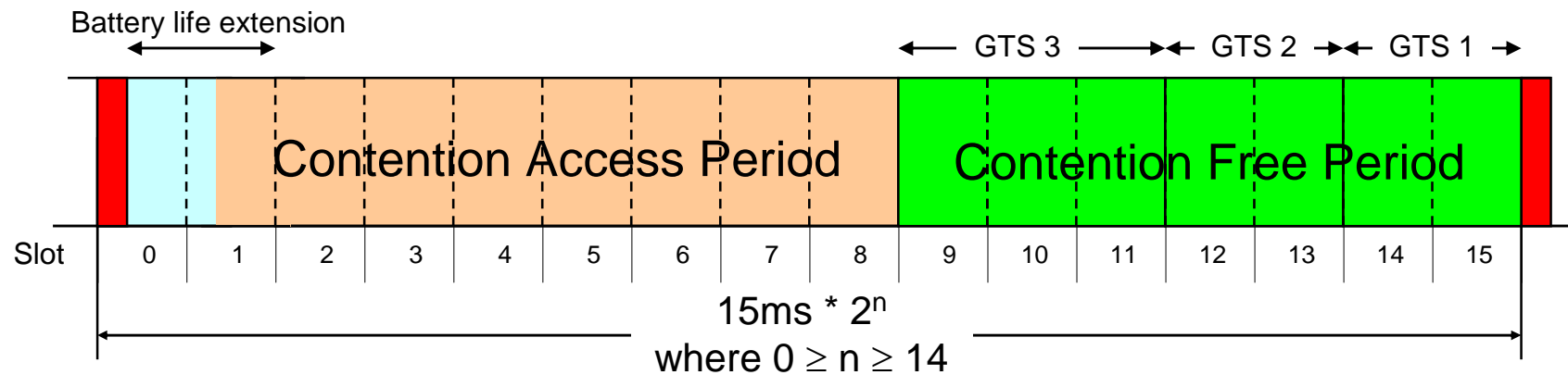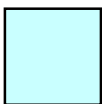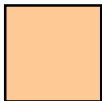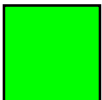
Network beacon	🟥	Transmitted by PAN coordinator. Contains network information, frame structure and notification of pending node messages.
Beacon extension period	🟦	Space reserved for beacon growth due to pending node messages
Contention period	🟧	Access by any node using CSMA-CA
Guaranteed Time Slot	🟩	Reserved for nodes requiring guaranteed bandwidth [n = 0].

IEEE 802.15.4 MAC
Superframe Structure 2

- ## Superframe with inactive period

SO = Superframe order
BO = Beacon order

Inactive Period

$15ms * 2^{SO}$
where $0 \geq SO \geq 14$

$15ms * 2^{BO}$
where $SO \geq BO \geq 14$
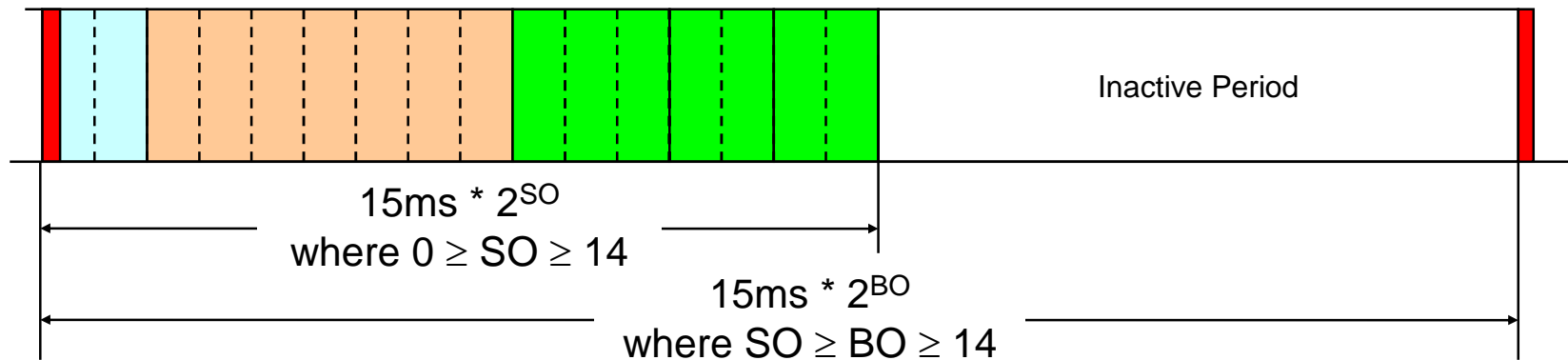
- ## Superframe without GTSs

Contention Access Period

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
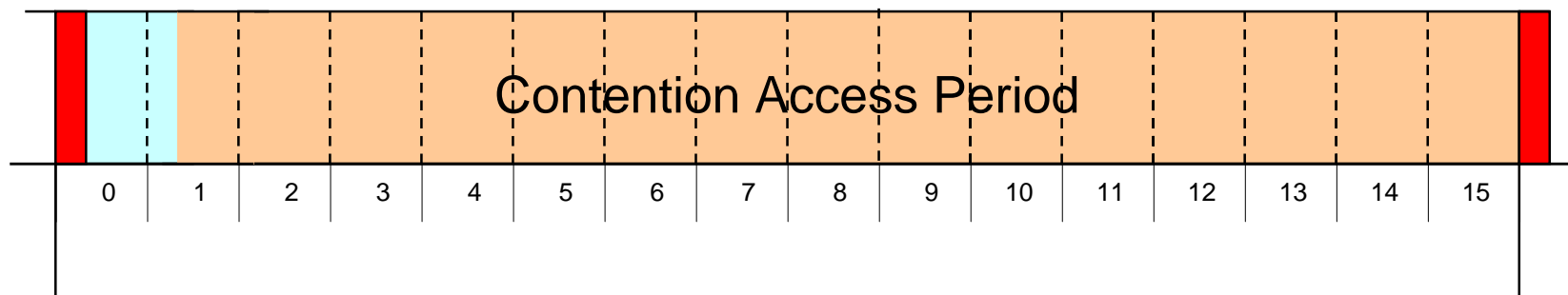
IEEE 802.15.4 MAC
Frame Formatting [1]

- **General MAC Frame**

		Payload	
MAC Layer	MAC Header (MHR)	MAC Service Data Unit (MSDU)	MAC Footer (MFR)

PHY Layer	Synch. Header (SHR)	PHY Header (PHR)	MAC Protocol Data Unit (MPDU)
			PHY Service Data Unit (PSDU)
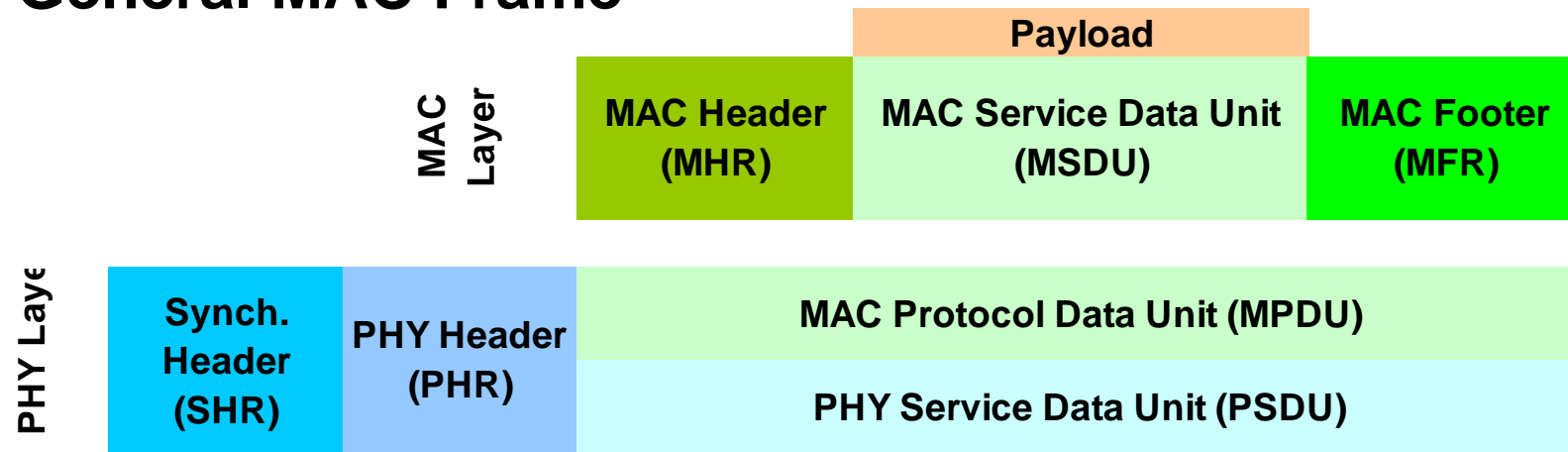
4 Types of MAC Frames:

- Data Frame

- Beacon Frame

- Acknowledgment Frame

- MAC Command Frame

- Maximum data length (MSDU)
  - *aMaxMACFrameSize* (102 bytes)

IEEE 802.15.4 MAC
Frame Formatting 2

● **General MAC Frame**

Octets:2	1	0/2	0/2/8	0/2	0/2/8	variable	2
Frame control	Sequence number	Destination PAN identifier	Destination address	Source PAN identifier	Source address	Frame payload	Frame check sequence
		Addressing fields					
MAC header						MAC payload	MAC footer

Bits: 0-2	3	4	5	6	7-9	10-11	12-13	14-15
Frame type	Security enabled	Frame pending	Ack. Req.	Intra PAN	Reserved	Dest. addressing mode	Reserved	Source addressing mode

Frame control field

IEEE 802.15.4 MAC
Frame Formatting 3

- **Beacon Frame**

Octets:2	1	4 or 10	2	variable	variable	variable	2
Frame control	Beacon sequence number	Source address information	Superframe specification	GTS fields	Pending address fields	Beacon payload	Frame check sequence
MAC header			**MAC payload**				**MAC footer**

Bits: 0-3	4-7	8-11	12	13	14	15
Beacon order	Superframe order	Final CAP slot	Battery life extension	Reserved	PAN coordinator	Association permit

IEEE 802.15.4 MAC
Frame Formatting 4

- **MAC Command Frame**

  - Command Frame Types
    - Association request
    - Association response
    - Disassociation notification
    - Data request
    - PAN ID conflict notification
    - Orphan Notification
    - Beacon request
    - Coordinator realignment
    - GTS request

Octets:2	1	4 to 20	1	variable	2
Frame control	Data sequence number	Address information	Command type	Command payload	Frame check sequence
MAC header			MAC payload		MAC footer

IEEE 802.15.4 MAC
Frame Formatting 5

- **Data Frame**

Octets:2	1	4 to 20	variable	2
Frame control	Data sequence number	Address information	Data payload	Frame check sequence
MAC header			**MAC Payload**	**MAC footer**

- **Acknowledgement Frame**

Octets:2	1	2
Frame control	Data sequence number	Frame check sequence
MAC header		**MAC footer**

IEEE 802.15.4 MAC
Architecture and Interaction
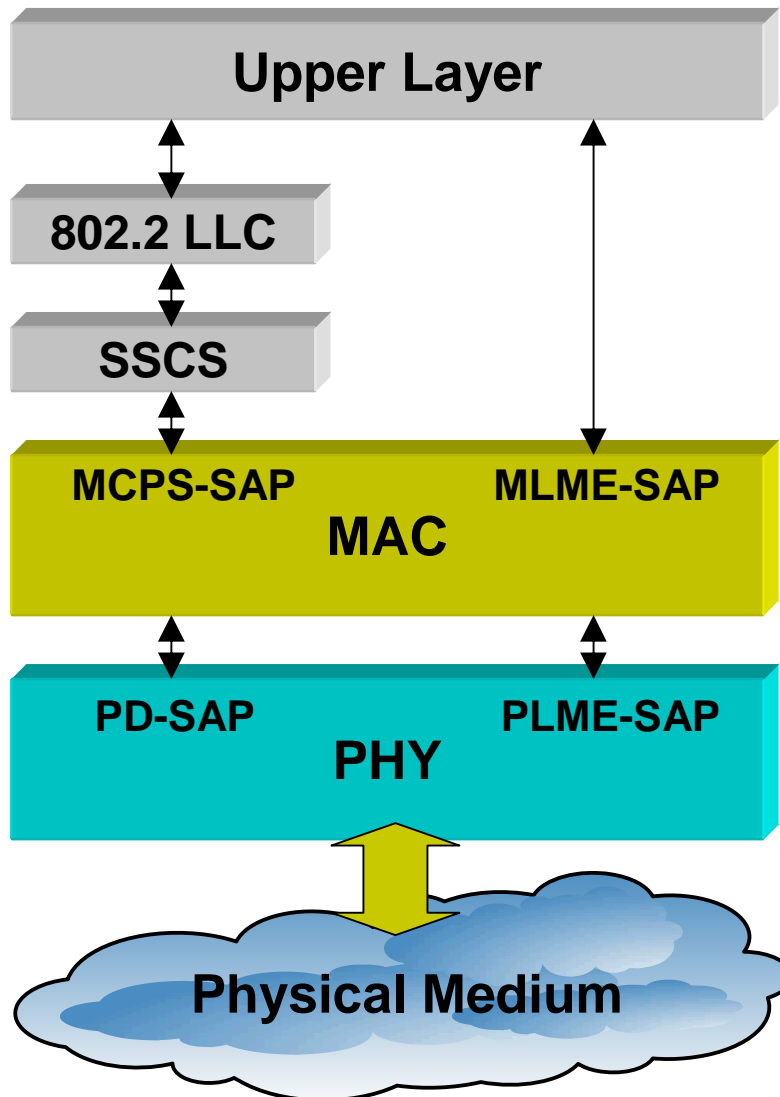
- MCPS
  - MAC common part sublayer

- MLME
  - MAC sublayer management entity

- PD
  - PHY data

- PLME
  - PHY layer management entity

IEEE 802.15.4 MAC
Concept of Primitives

Service Provider
(N-layer)

Service User
(N-User)

Service User
(N-User)

Request ———————→

→ Indication

← Response

Confirm ←———————
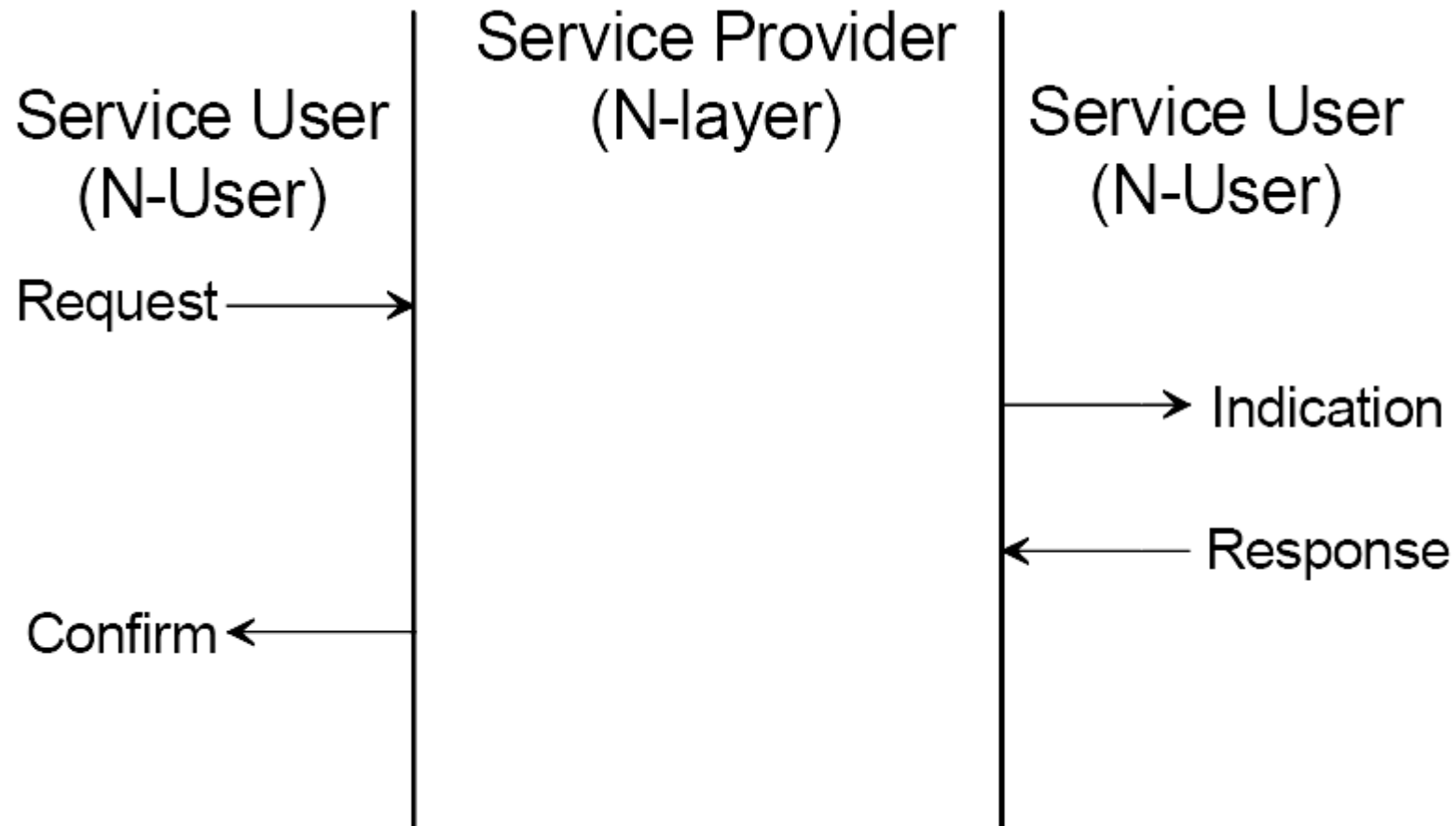
IEEE 802.15.4 MAC
PHY Primitives

- **PHY Data Service**

  - PD-DATA – exchange data packets between MAC and PHY

- **PHY Management Service**

  - PLME-CCA – clear channel assessment

  - PLME-ED - energy detection

  - PLME-GET / -SET– retrieve/set PHY PIB parameters

  - PLME-TRX-ENABLE – enable/disable transceiver

IEEE 802.15.4 MAC
MAC Primitives

- **MAC Data Service**
  - MCPS-DATA – exchange data packets between MAC and PHY
  - MCPS-PURGE – purge an MSDU from transaction queue

- **MAC Management Service**
  - MLME-ASSOCIATE/DISASSOCIATE – network association
  - MLME-SYNC / SYNC-LOSS - device synchronization
  - MLME-SCAN - scan radio channels
  - MLME-GET / -SET– retrieve/set MAC PIB parameters
  - MLME-START / BEACON-NOTIFY – beacon management
  - MLME-POLL - beaconless synchronization
  - MLME-GTS - GTS management
  - MLME-ORPHAN - orphan device management
  - MLME-RX-ENABLE - enabling/disabling of radio system

IEEE 802.15.4 MAC
MAC Data Primitives

Primitive	Request	Confirm	Indication	Response
MCPS-DATA	Required	Required	Required	
MCPS-PURGE	Optional for RFD	Optional for RFD		

IEEE 802.15.4 MAC
Data Transfer

Originator higher layer	Originator MAC	Recipient MAC	Recipient higher layer

MCPS-DATA.request →

Data frame →

← *Acknowledgment* (if requested)

MCPS-DATA.indication →

← MCPS-DATA.confirm
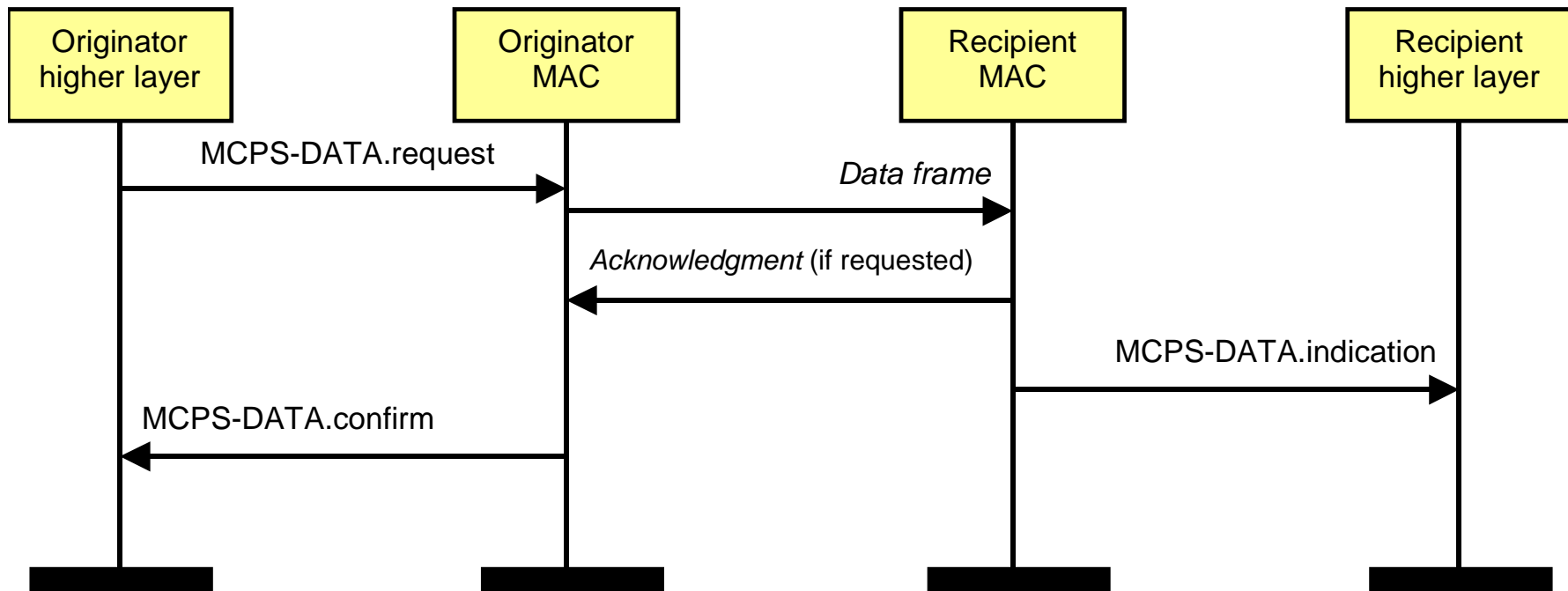
IEEE 802.15.4 MAC
Indirect Data Transfer

IEEE 802.15.4 MAC
MAC Management Primitives

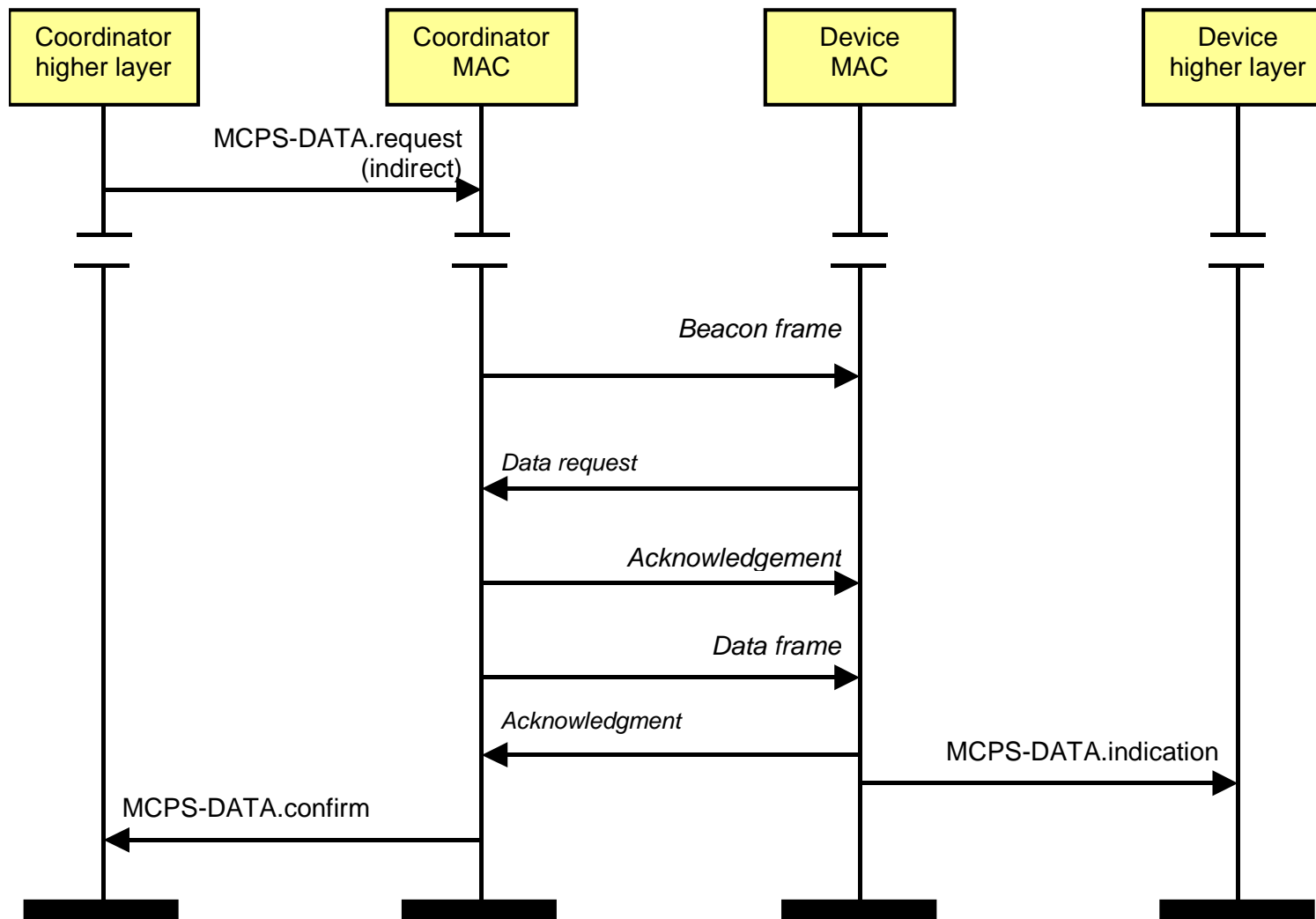| Primitive	Request	Confirm	Indication	Response
MLME-GET	Required	Required		
MLME-SET	Required	Required		
MLME-ASSOCIATE	Required	Required	Optional for RFD	Optional for RFD
MLME-DISASSOCIATE	Required	Required	Required	
MLME-GTS	Optional for RFD	Optional for RFD	Optional for RFD	
MLME-BEACON-NOTIFY			Required	
MLME-POLL	Required	Required		
MLME-COMM-STATUS			Required	
MLME-ORPHAN			Optional for RFD	Optional for RFD
MLME-SCAN	Required	Required		
MLME-START	Optional for RFD	Optional for RFD		
MLME-RX-ENABLE	Required	Required		
MLME-SYNC	Required			
MLME-SYNC-LOSS			Required	
MLME-RESET	Required	Required		

IEEE 802.15.4 MAC
Association

Device higher layer	Device MAC	Coordinator MAC	Coordinator higher layer

MLME-ASSOCIATE.request

Association request

Acknowledgment

MLME-ASSOCIATE.indication

aResponseWaitTime

MLME-ASSOCIATE.response

Data request

Acknowledgment

Association response

Acknowledgement

MLME-ASSOCIATE.confirm

MLME-COMM-STATUS.indication
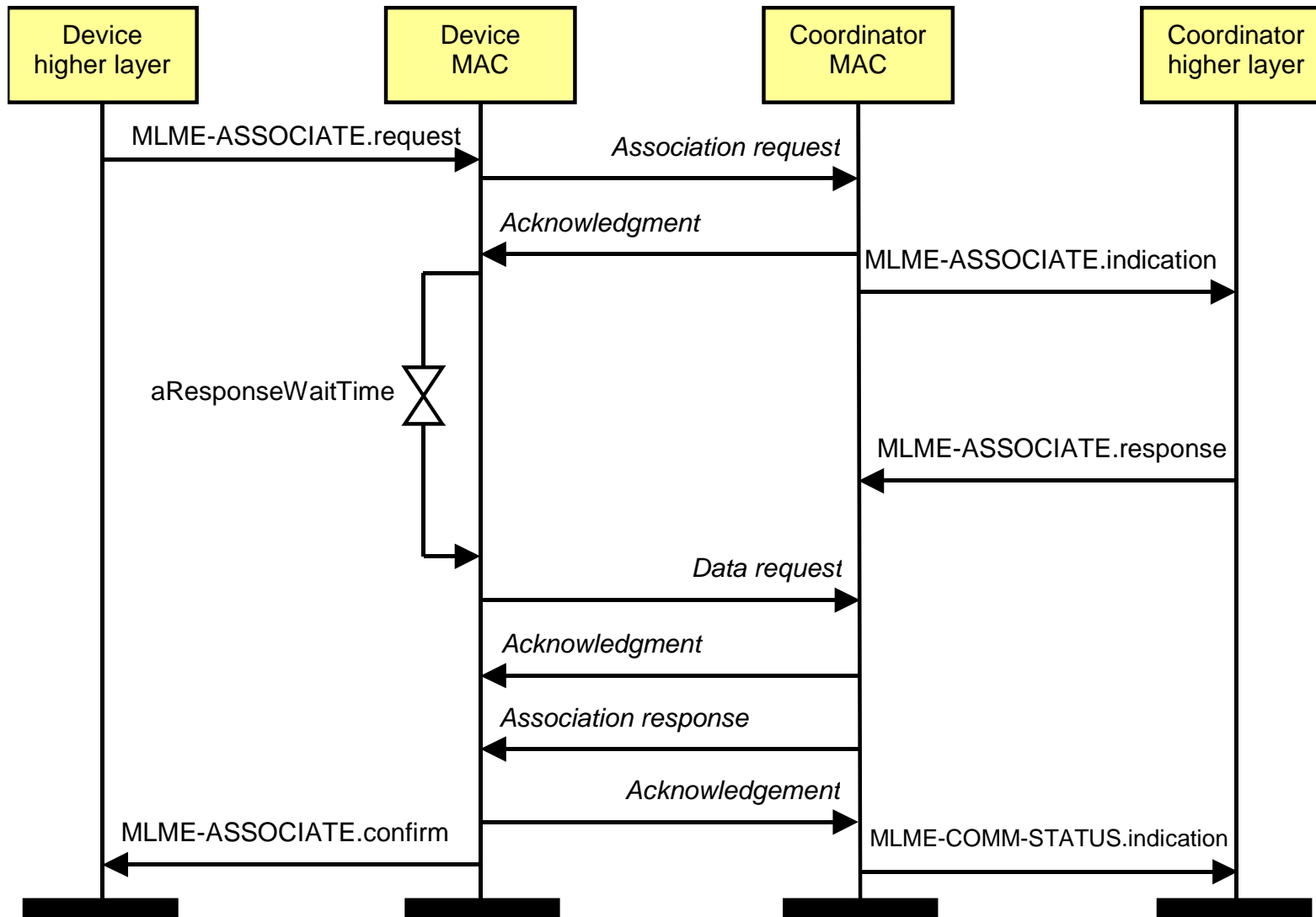
IEEE 802.15.4 MAC
Disassociation

Originator higher layer	Originator MAC	Recipient MAC	Recipient higher layer

MLME-DISASSOCIATE.request →

Disassociation notification →

← *Acknowledgment*

← MLME-DISASSOCIATE.confirm

MLME-DISASSOCIATE.indication →

IEEE 802.15.4 MAC
Data Polling

```
Device              Device              Coordinator
higher layer        MAC                 MAC
```

MLME-POLL.request →

Data request →

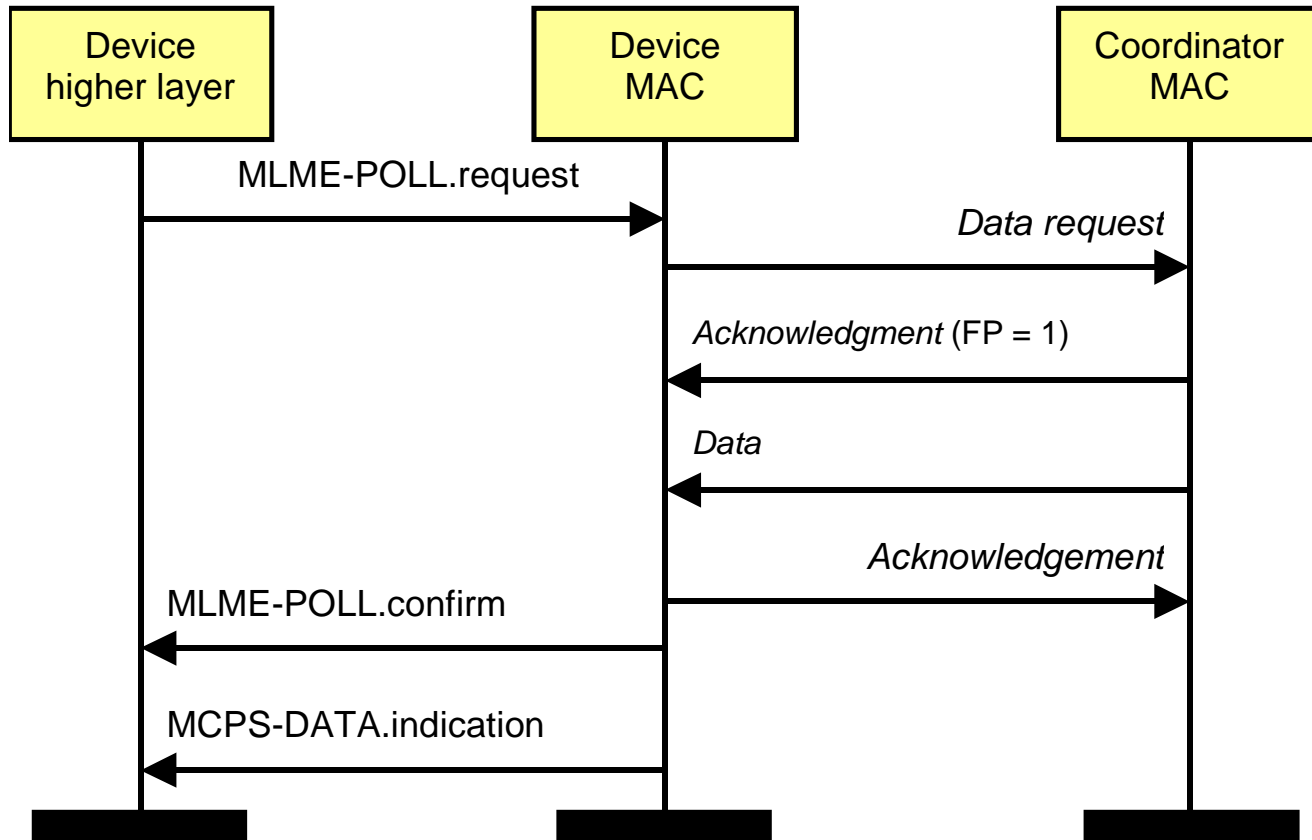← Acknowledgment (FP = 0)

← MLME-POLL.confirm
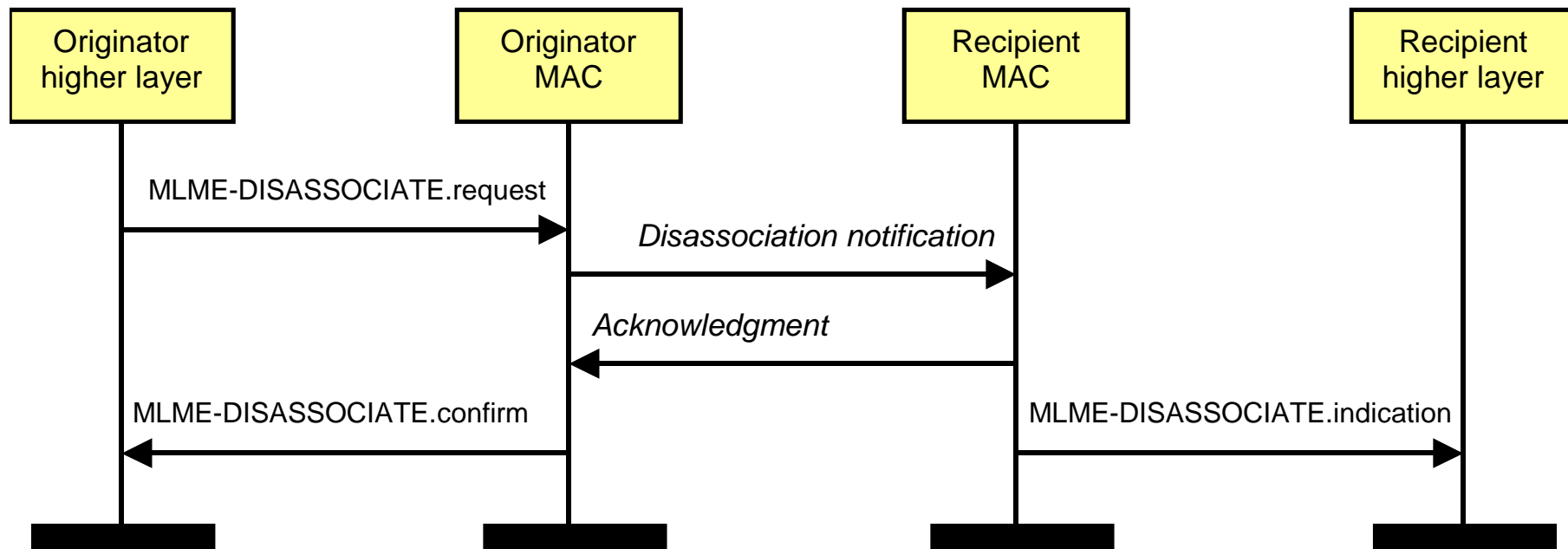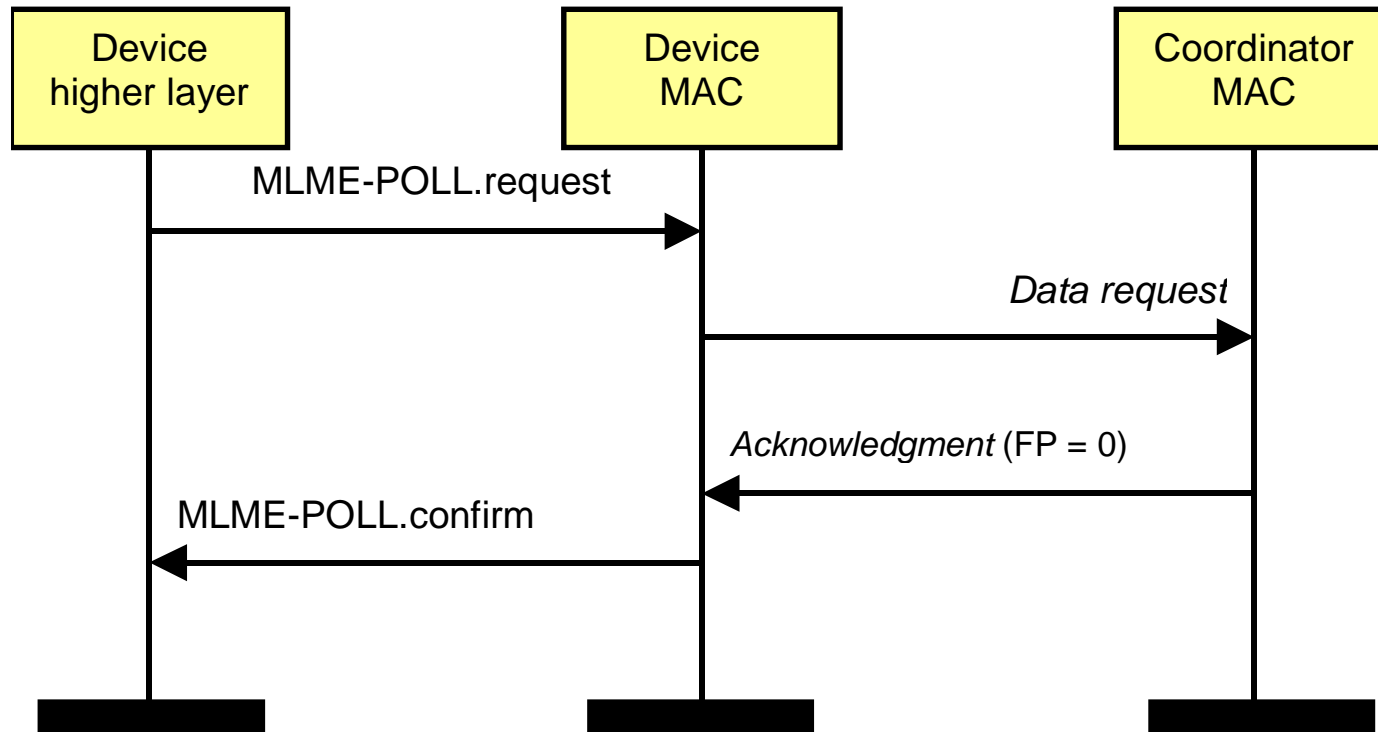
No data pending at the coordinator

IEEE 802.15.4 MAC
Data Polling
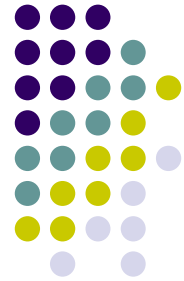
Data pending at the coordinator

IEEE 802.15.4 MAC
Passive Scan

Device higher layer | Device MAC | Coordinator MAC

MLME-SCAN.request

Set 1st Channel

ScanDuration

Beacon

Set 2nd Channel

MLME-SCAN.confirm
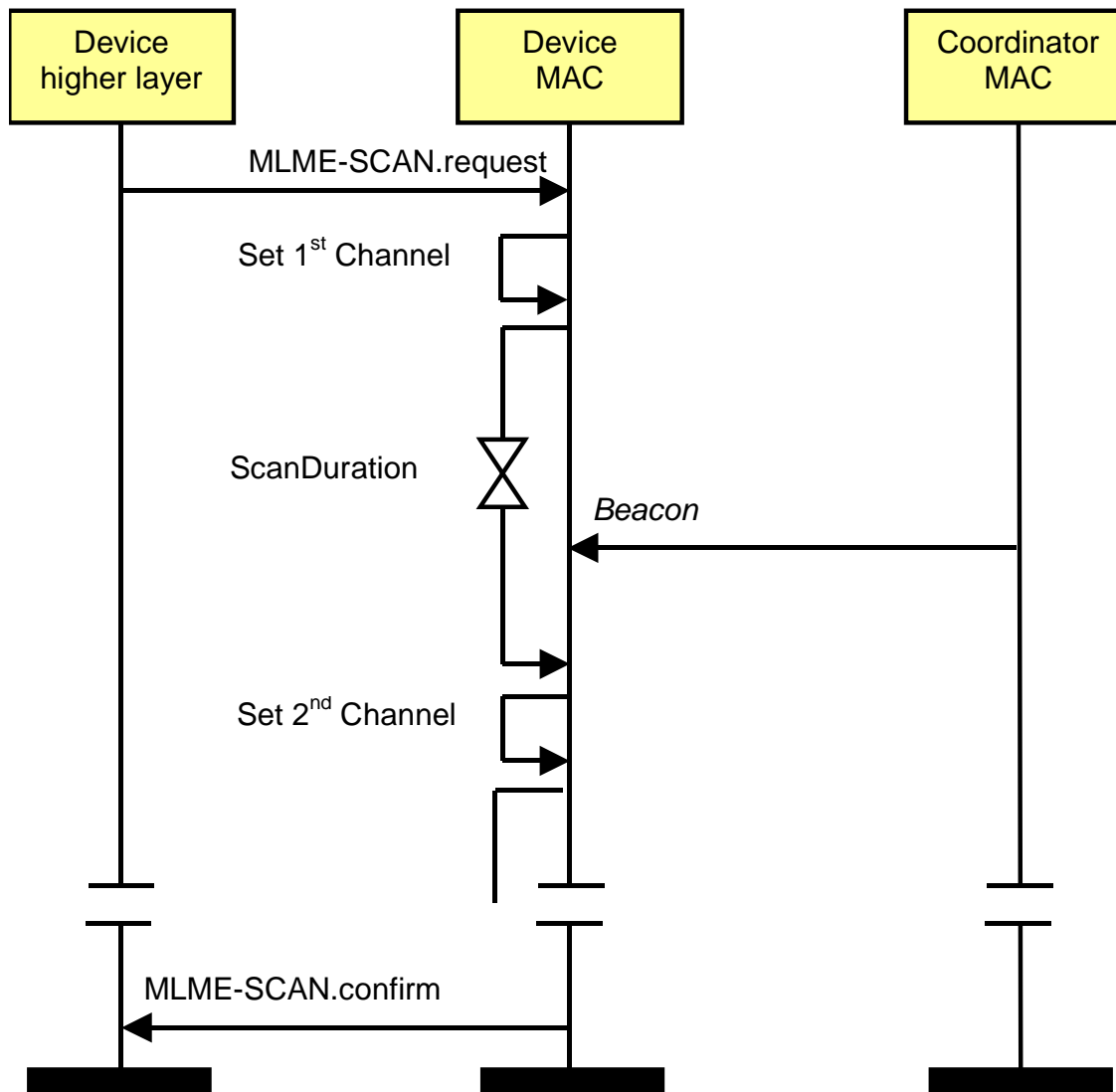
IEEE 802.15.4 MAC
Active Scan

Device higher layer → Device MAC: MLME-SCAN.request

Device MAC: Set 1st Channel

Device MAC → Coordinator MAC: *Beacon request*

Coordinator MAC: CSMA

ScanDuration

Coordinator MAC → Device MAC: *Beacon*

Device MAC: Set 2nd Channel

Device MAC → Coordinator MAC: *Beacon request*

Device MAC → Device higher layer: MLME-SCAN.confirm
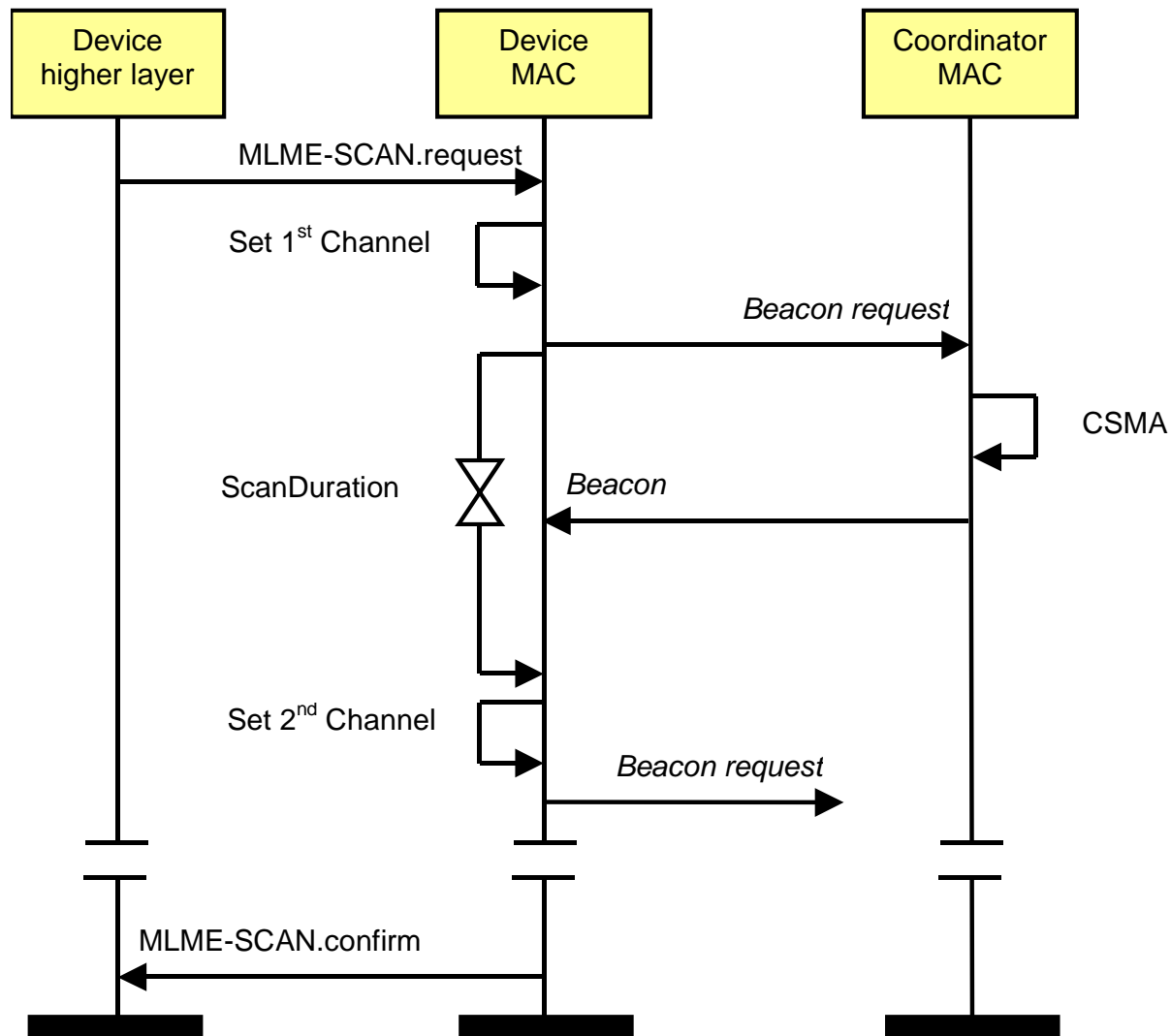
IEEE 802.15.4 MAC
Orphaning
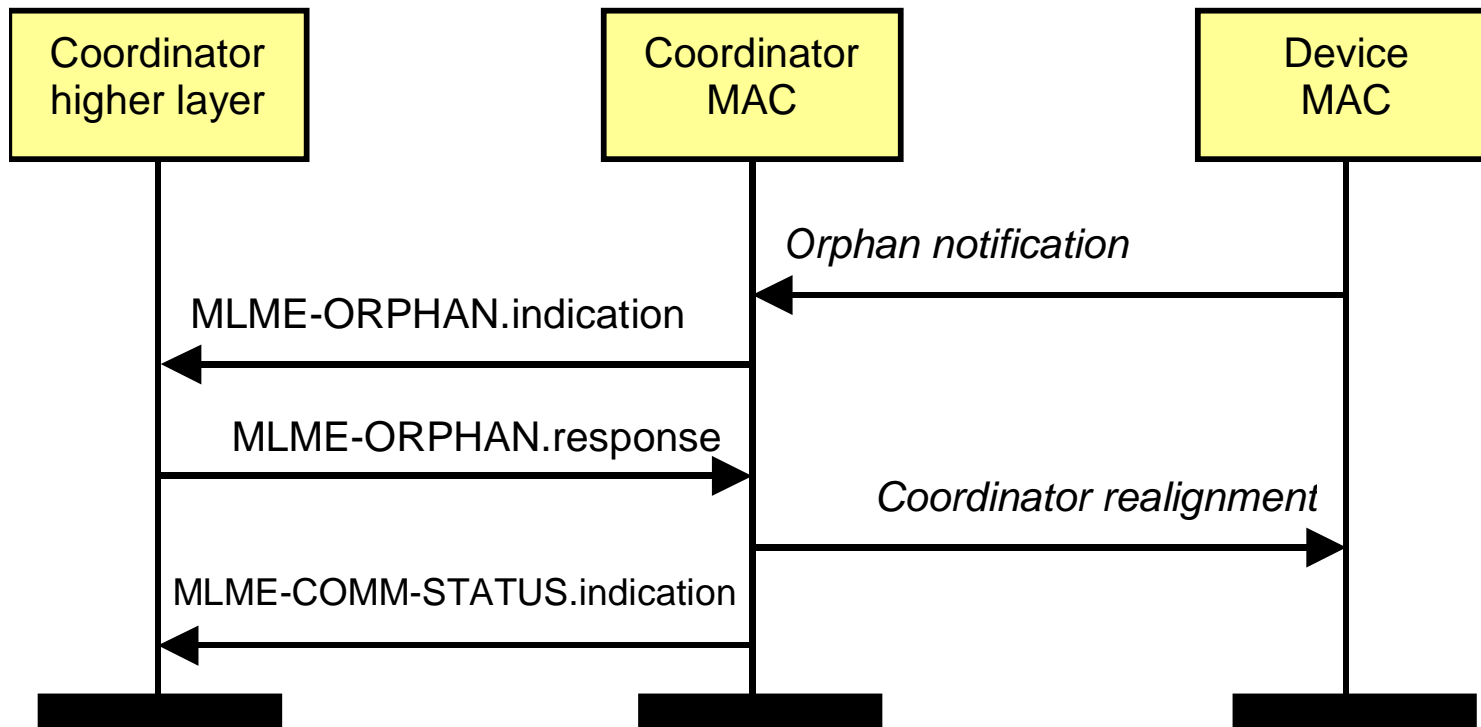
IEEE 802.15.4 MAC
Inter-frame Spacing

Acknowledged transmission

| Long frame |

ACK   Short frame   ACK

t_{ack} LIFS t_{ack} ~~SIFS~~
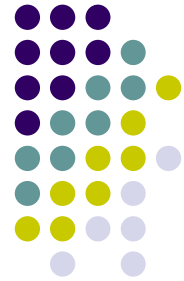
Unacknowledged transmission

Long frame   Short frame

LIFS   ~~SIFS~~

$aTurnaroundTime \leq t_{ack} \leq (aTurnaroundTime$ (12 symbols) $+ aUnitBackoffPeriod$ (20 symbols))
LIFS $> aMaxLIFSPeriod$ (40 symbols)
SIFS $> aMaxSIFSPeriod$ (12 symbols)

For frames $\leq aMaxSIFSFrameSize$ use short inter-frame spacing (SIFS)
For frames $> aMaxSIFSFrameSize$ use long inter-frame spacing (LIFS)

IEEE 802.15.4 MAC
Slotted CSMA-CA Procedure

Used in beacon enabled networks.

```
                Slotted CSMA

                NB = 0, CW = 0
                      │
                      ▼
               Battery life ──Y──▶  BE = lesser of
               extension?           (2, macMinBE)
                      │
                      N
                      ▼
               BE = macMinBE
                      │
                      ▼
              Locate backoff
              period boundary

        Delay for
        random(2^BE - 1) unit
        backoff periods
              │
              ▼
        Perform CCA on
        backoff period
        boundary
              │
              ▼
         Channel idle? ──Y──▶  CW = CW - 1
              │                      │
              N                      ▼
              ▼                  CW = 0? ──N──▶
    CW = 2, NB = NB+1,              │
    BE = min(BE+1, aMaxBE)          Y
              │                      ▼
              ▼                   Success
         NB>
    macMaxCSMABackoffs ──N──▶ (loop back)
         ?
         │
         Y
         ▼
      Failure
```
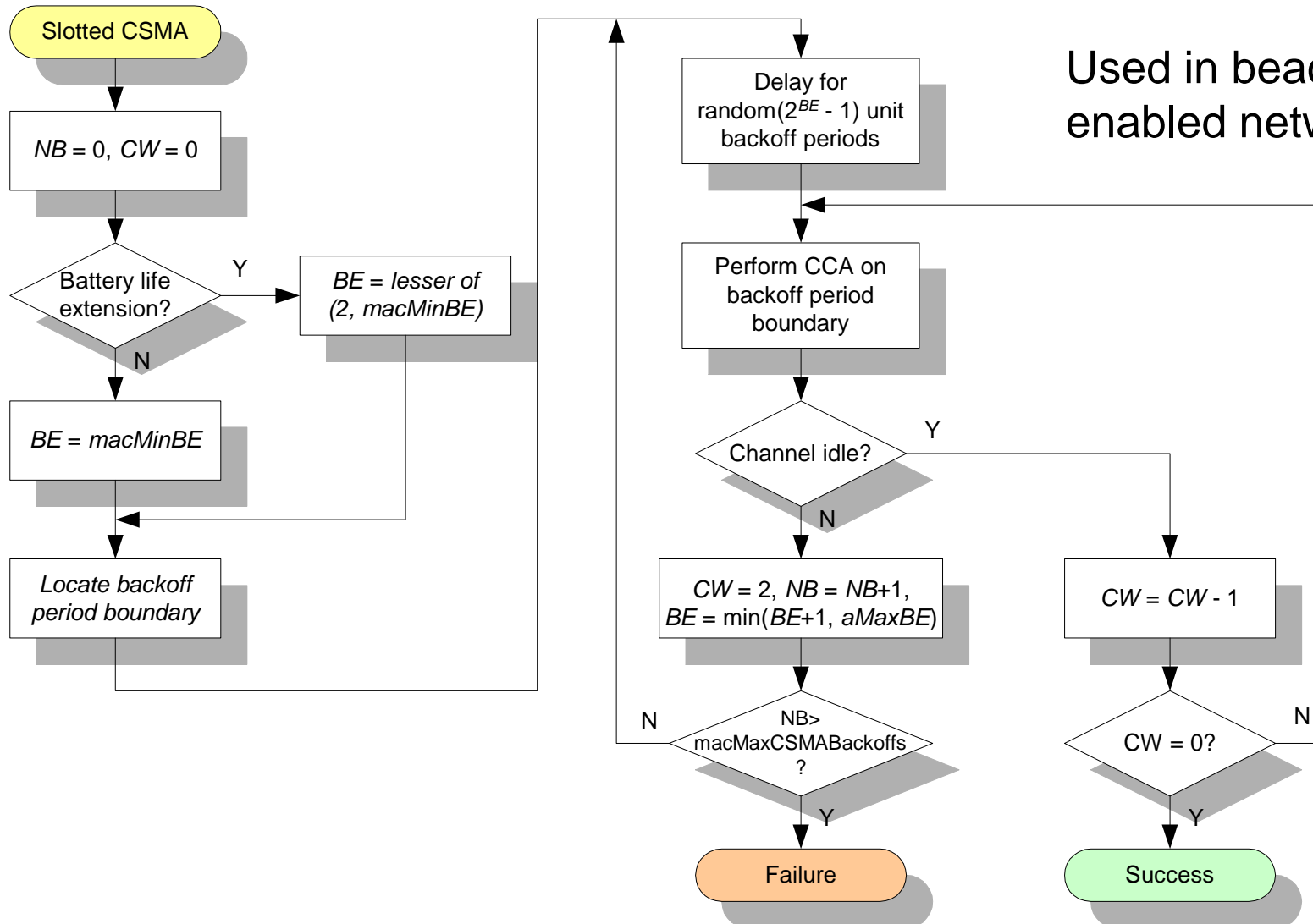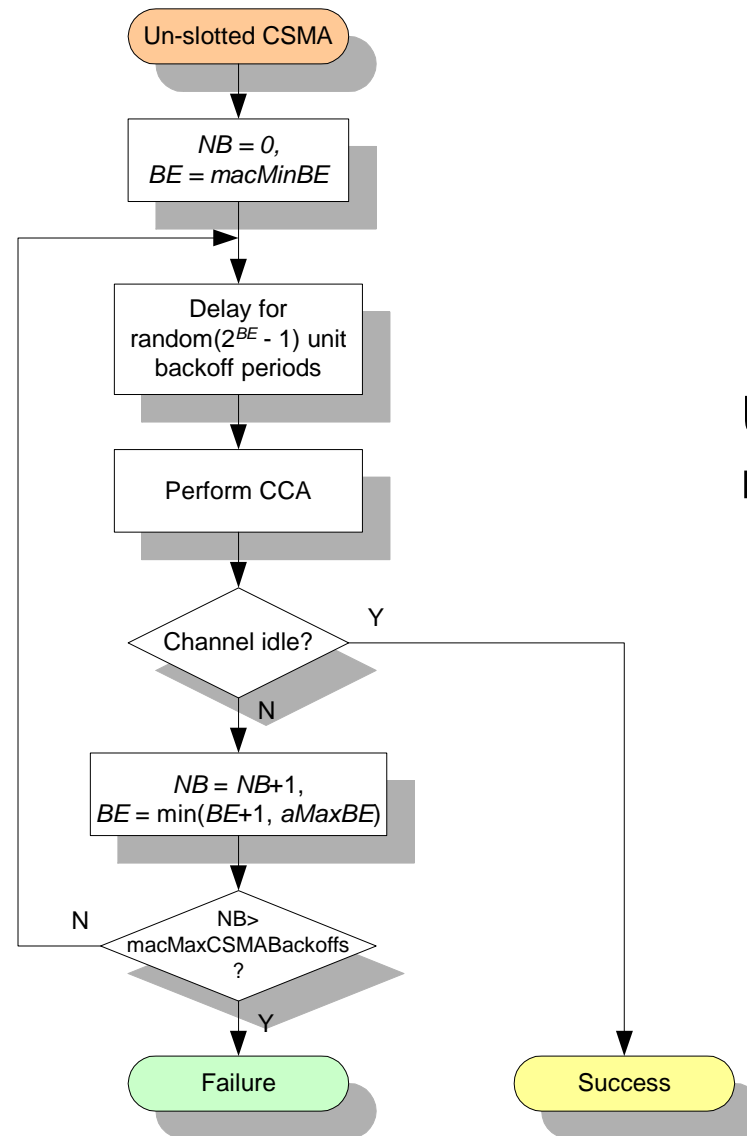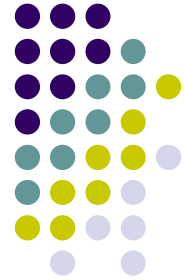
$BE = lesser\ of\ (2, macMinBE)$

$Delay\ for\ random(2^{BE} - 1)\ unit\ backoff\ periods$

$CW = 2,\ NB = NB+1,\ BE = \min(BE+1,\ aMaxBE)$

IEEE 802.15.4 MAC
Un-slotted CSMA-CA Procedure

Un-slotted CSMA

$NB = 0,$
$BE = macMinBE$

Delay for random$(2^{BE} - 1)$ unit backoff periods

Perform CCA

Channel idle?

Y

N

$NB = NB+1,$
$BE = \min(BE+1, aMaxBE)$

$NB > macMaxCSMABackoffs$?

N

Y

Failure

Success

Used in non-beacon networks.

References

- IEEE Standard for Part 15.4: Wireless Medium Access Control Layer (MAC) and Physical Layer (PHY) specifications for Low Rate Wireless Personal Area Networks (LR-WPANs), IEEE Std 802.15.4™-2006

- Jose Gutierrez, IEEE 802.15.4 Tutorial, Available: www.ieee802.org/15/pub/2003/Jan03/03036r0P802-15_WG-802-15-4-TG4-Tutorial.ppt

- Marco Naeve (4 January, 2003), IEEE 802.15.4 MAC Overview, Available: ftp://ieee:wireless@ftp.802wirelessworld.com/15/04/15-04-0218-01-004a-ieee802-15-4-mac-overview.ppt