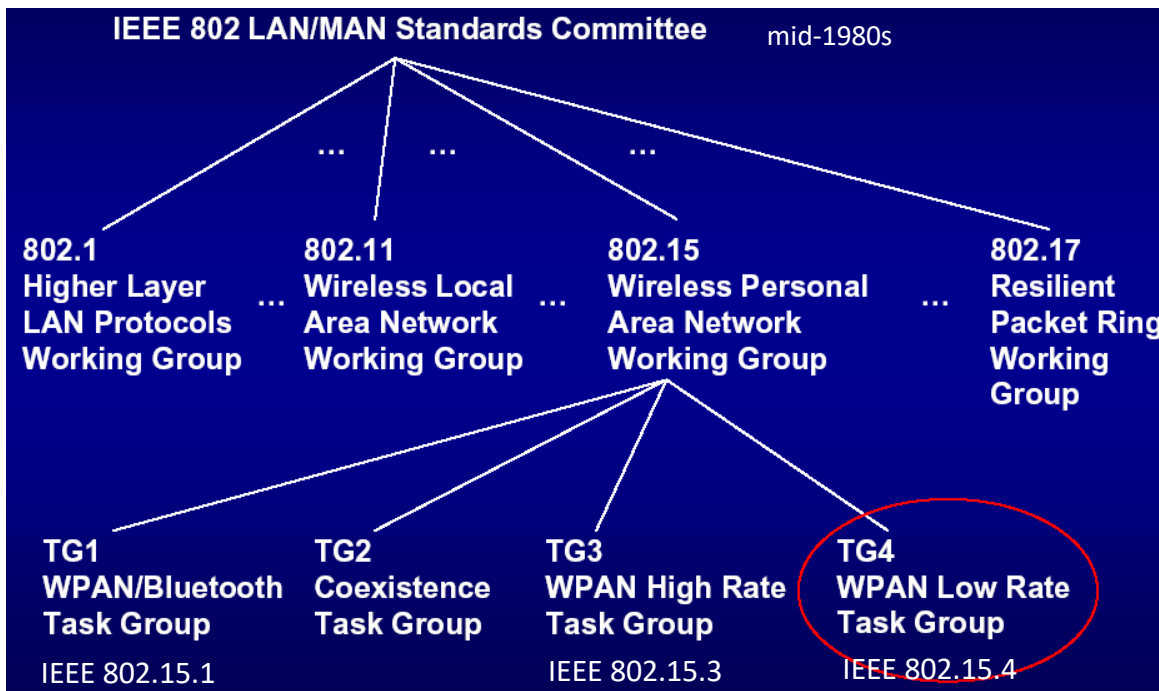


IEEE 802.15 Working Group

- IEEE 802.11 was concerned with features like
 - Ethernet like speed
 - Medium range (~100 m) communication
 - Seamless roaming
 - Less complex message forwarding
 - Data throughput ~ 2-11 Mbps
- IEEE 802.15 are focused to
 - Short range
 - space around a person or a object (~ 10 m)
 - Low cost
 - Low power
 - Very small packet size

IEEE 802.15 working group mainly defines three standards:

1. **High data rate WPAN**
 - IEEE 802.15.3
 - e.g. for multimedia applications
2. **Medium rate WPAN**
 - IEEE 802.15.1 / Bluetooth
 - e.g. for device to device communication
3. **Low rate WPAN**
 - IEEE 802.15.4
 - e.g. relaxed data rate, and battery powered device



IEEE 802.15 - Task Group 4



- TG4 was formed to define
 - low-data-rate PHY and MAC layer specifications for **wireless personal area networks (WPAN)**
- standard has evolved over time:
 - IEEE 802.15.4-2003 ; IEEE 802.15.4-2006
 - IEEE 802.15.4-2011; **IEEE 802.15.4-2015**
 - IEEE 802.15.4-2020
- WPAN
 - span a **small area**
 - e.g., a private home or an individual workspace
 - **short distance** communication
 - **low-powered** communication
 - e.g. lifetime must be few months or years
 - primarily uses **ad-hoc networking**
 - Generally **wireless**; could be **wired**
 - Intended to serve industrial, residential and medical applications

IEEE 802.15.4 LR-WPAN



- A **low-rate wireless personal area network** (LR-WPAN) is a
 - ✓ simple,
 - ✓ **low-cost** communication network
 - ✓ that allows **wireless** connectivity in applications
 - ✓ with **limited power** and
 - ✓ **relaxed throughput** requirements.

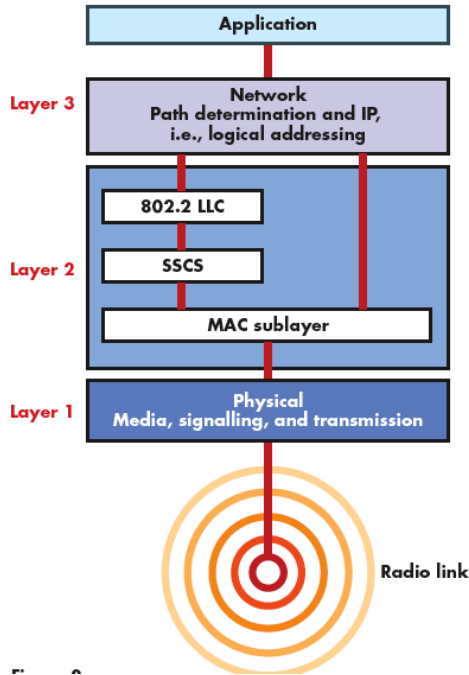
- The **main objectives** of an LR-WPAN are
 - ✓ ease of installation,
 - ✓ reliable data transfer,
 - ✓ extremely low cost,
 - ✓ a reasonable battery life,
 - ✓ while maintaining a simple and flexible protocol.

Reference: IEEE Std 802.15.4™-2020, “IEEE Standard for **Low-Rate Wireless Networks**”,
Developed by the LAN/MAN Standards Committee of the IEEE Computer Society, Approved on 6 May 2020.

IEEE 802.15.4 Stack – PHY & MAC



The OSI model adapted to the IEEE 802.15.4



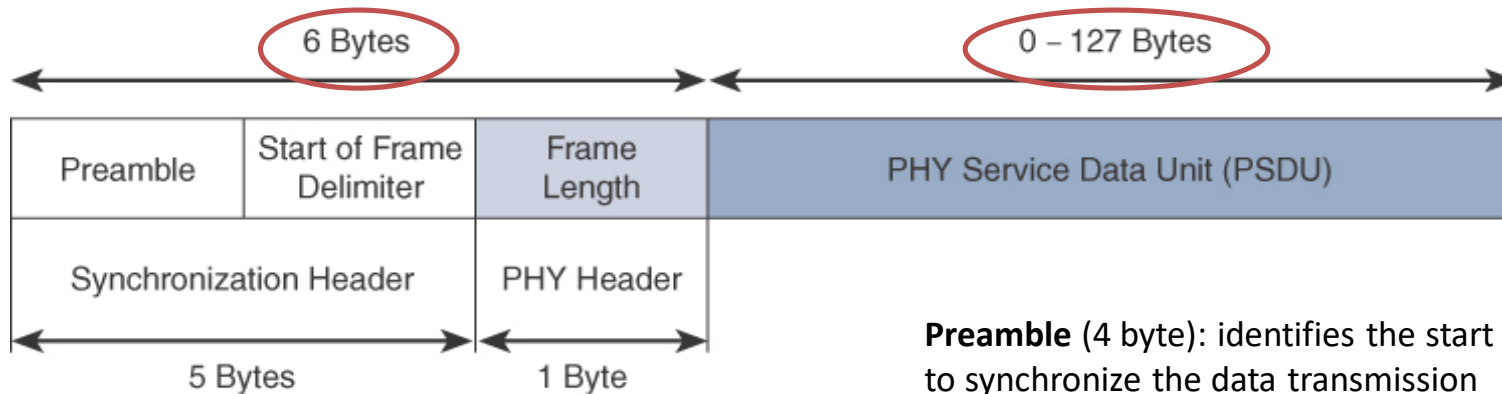
LLC: Logical Link Control – provides protocol multiplexing
SSCS: Service Specific Convergence Sublayer

- IEEE 802.15.4 standard is limited to the **PHY & MAC** Layers
- IEEE 802.15.4 standard PHY provides the **PHY data service** and **PHY management services**:
 - The **PHY data service** enables the **transmission** and **reception** of PHY protocol data units (PPDU) across the physical radio channel.
 - The **PHY's features** include
 - radio transceiver activation/deactivation,
 - radio channel selection,
 - energy level detection (ED) ,
 - received signal quality (RSI) or link quality indicator (LQI),
 - clear channel assessment (CCA),
 - channel selection
 - transmitting and receiving packets in 2.4-GHz band.
- IEEE 802.15.4 standard MAC provides the **MAC data service** and **MAC management services**.
 - The **MAC data service** enables **transmission** of MAC protocol data units (MPDU) across the PHY data service.
 - The **MAC sublayer features** include
 - beacon management,
 - channel access,
 - GTS management,
 - frame validation,
 - ACK frame delivery, and
 - association and disassociation.

Image Source: <https://www.embedded.com/ieee-802-15-4-zigbee-hardware-and-software-open-the-applications-window/>

IEEE 802.15.4 PHY

IEEE 802.15.4 PHY Layer



IEEE 802.15.4 PHY Frame Format

Preamble (4 byte): identifies the start of the frame; used to synchronize the data transmission

SFD (1 byte): informs the receiver about the starting point of frame content. It shall be formatted as “1110 0101”

PHY functionalities:

- **Activation & deactivation** of the radio transceiver
- **Energy level detection (ED)** within the current channel
- **Link quality indication (LQI)** or **received signal quality (RSI)** for received packets
- **Clear channel assessment (CCA)** for CSMA-CA
- **Channel frequency selection**
- Data packet **transmission** and **reception** at given frequency

Spectrum



- Federal Communications of Commissions (FCC) in USA decides frequency bands
- Applications using ISM band do not require a licence for stations emitting less than 1W.

FCC Band	Max. Transmit Power	Frequencies
Industrial Band	< 1 W	902 MHz – 928 M Hz
Scientific Band	< 1 W	2.4 GHz – 2.48 GHz
Medical Band	< 1 W	5.725 GHz – 5.85 GHz
U-NII (Unlicensed National Information Infrastructure)	< 40 mW	5.15 GHz – 5.25 GHz
	< 200 mW	5.25 GHz – 5.35 GHz
	< 800 mW	5.725 GHz – 5.82 GHz

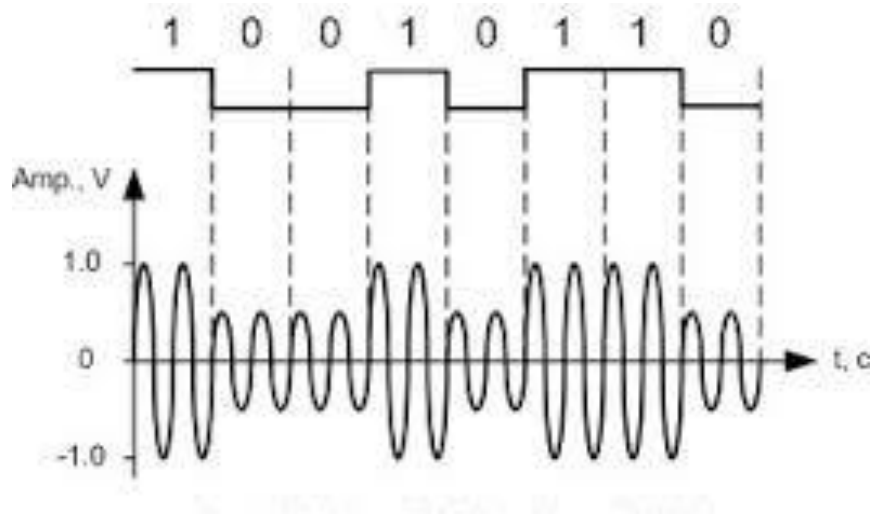
- Physical layer **transmission options** in IEEE 802.15.4-2015
 - **2.4 GHz**, 16 channels, data rate 250 kbps
 - **915 MHz**, 10 channels, data rate 250 kbps
 - **868 MHz**, 3 channel, data rate 100 kbps

Modulation

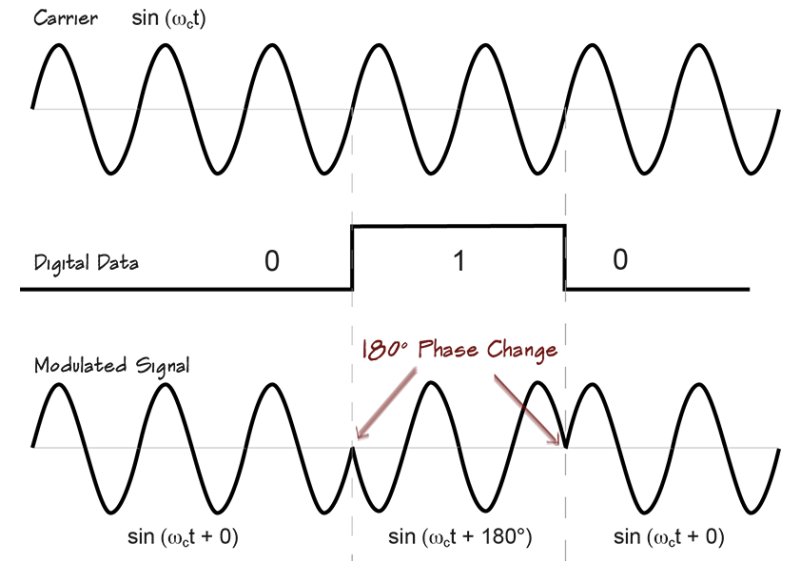
Modulation is the process by which some characteristic of a **carrier wave** is varied in accordance with an information/ **modulating signal**.

Modulation schemes

- **OQPSK PHY** : DSSS PHY employing Offset Quadrature Phase-Shift Keying (OQPSK)
- **BPSK PHY** : DSSS PHY employing binary phase-shift keying (BPSK)
- **ASK PHY** : PSSS PHY employing Amplitude Shift Keying (ASK) and BPSK

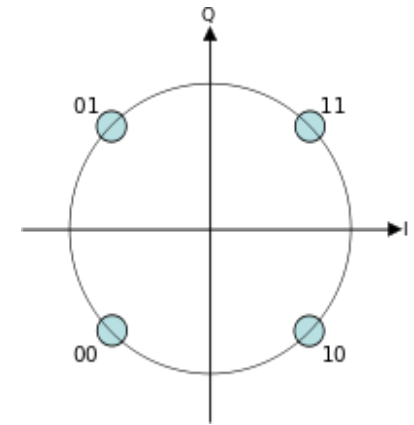
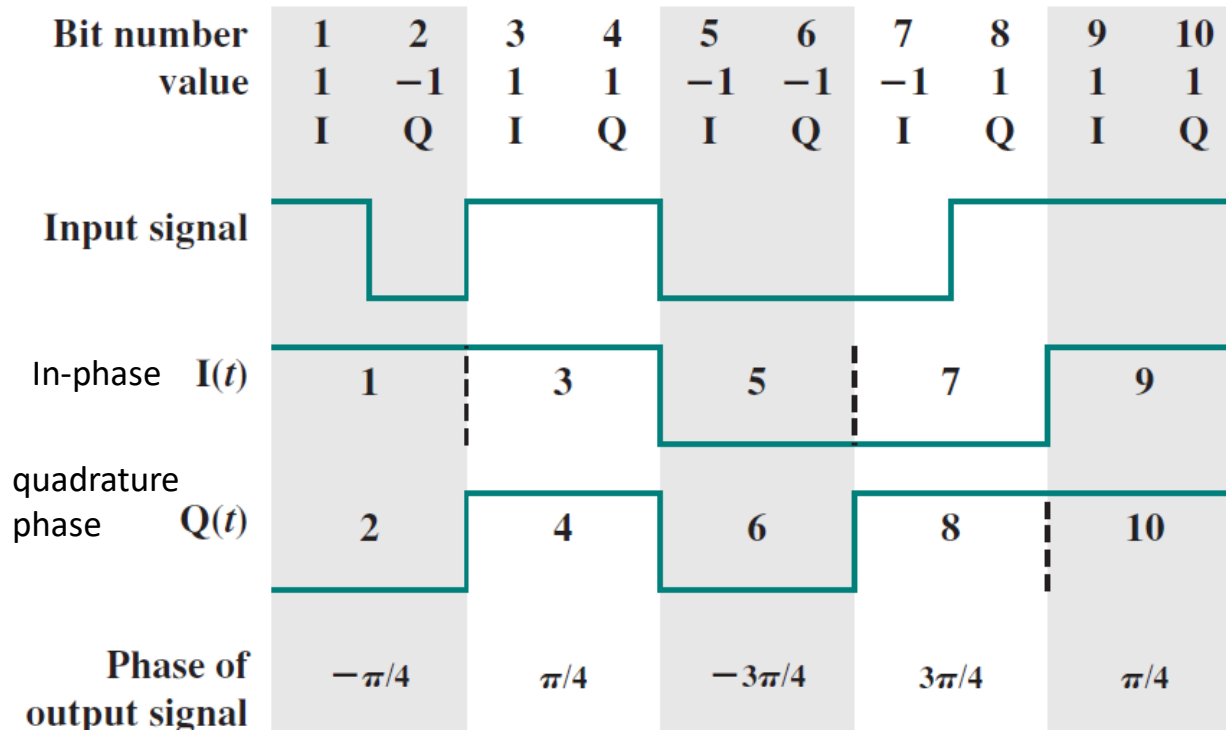


Amplitude Shift Keying (ASK)



Binary Phase-Shift Keying (BPSK)

QPSK



Constellation diagram for QPSK

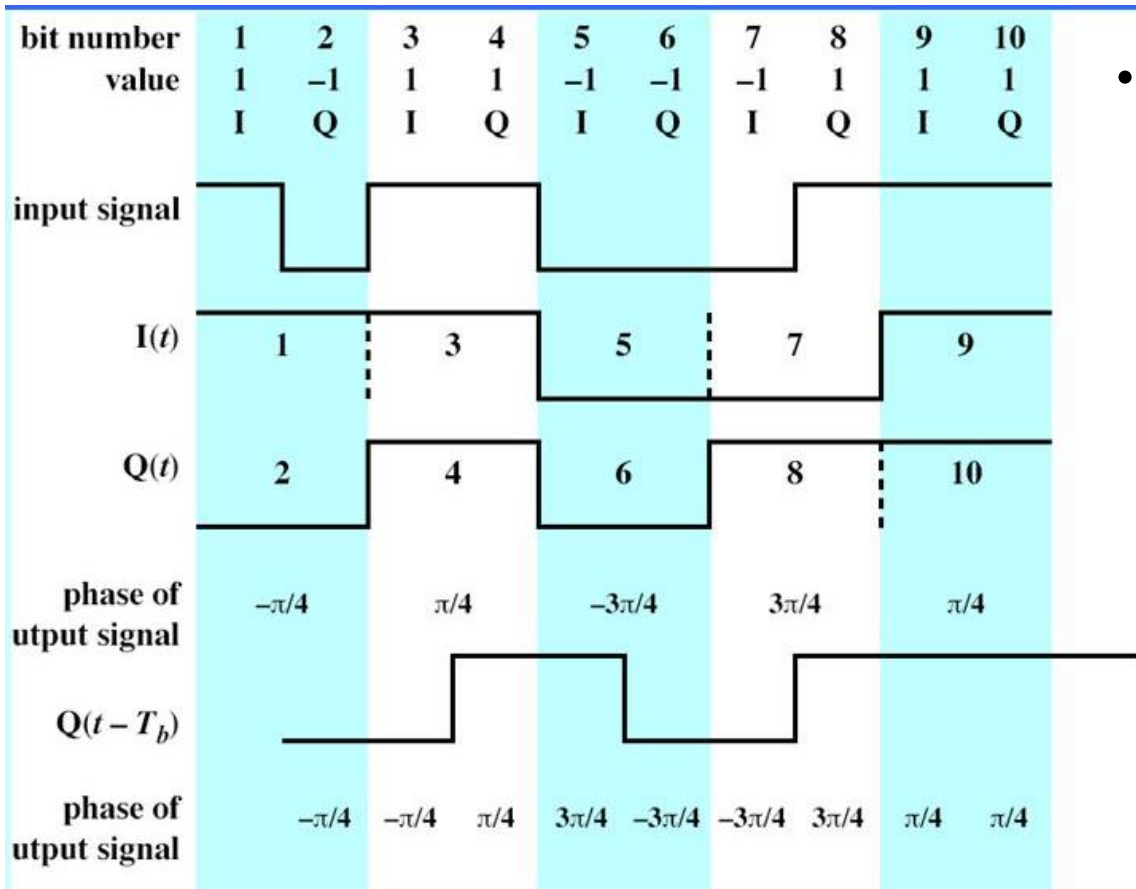
Quadrature Phase-Shift Keying (QPSK)

- More efficient use of bandwidth
 - as each signalling element represents more than one bit.

$$\text{QPSK } s(t) = \begin{cases} A \cos\left(2\pi f_c t + \frac{\pi}{4}\right) & 11 \\ A \cos\left(2\pi f_c t + \frac{3\pi}{4}\right) & 01 \\ A \cos\left(2\pi f_c t - \frac{3\pi}{4}\right) & 00 \\ A \cos\left(2\pi f_c t - \frac{\pi}{4}\right) & 10 \end{cases}$$

Orthogonal QPSK

- **Problem in QPSK:** large phase shift at high transition rate is difficult to perform. Phase shift is 180° in QPSK.



- **OQPSK**

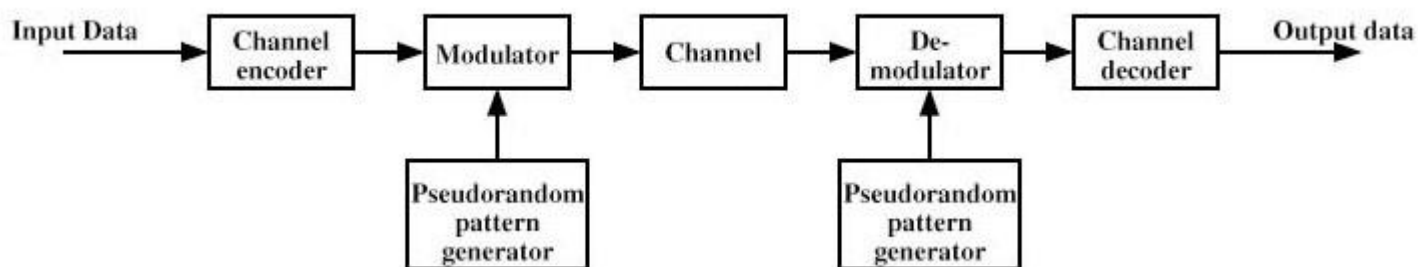
- ✓ a variation of QPSK known as **offset QPSK** or **orthogonal QPSK**
- ✓ a **delay of one bit time** is introduced in the Q stream of QPSK
- ✓ Its spectral characteristics and bit-error performance are the same as that of QPSK
- ✓ at any time the **phase change** in the combined signal **never exceeds 90° ($\pi/2$)**

Spread Spectrum



Spread Spectrum is a method of spreading a transmitted spectrum over a wide bandwidth, so that the **energy at any particular frequency is not detectable** without special foreknowledge of the spreading technique.

- Spread-spectrum transmission offers many advantages over a fixed-frequency transmission.
 - Spread-spectrum signals are highly resistant to narrow band interference
 - Signals are difficult to intercept, so immune to jamming
- **Types:**
 - direct sequence spread spectrum (**DSSS**)
 - frequency hopping spread spectrum (**FHSS**)



Cont...



- Pseudorandom numbers
 - generated by an algorithm using some initial value called the **seed**
 - produce sequences of numbers that are **not statistically random**, but passes reasonable tests of randomness
 - unless you know the **algorithm** and the **seed**, **it is impractical to predict the sequence**
- **Gain from this apparent waste of spectrum**
 - The signals **gains immunity** from various kinds of noise and multipath distortion.
 - **Immune to** jamming attack
 - It can also be used for **hiding and encrypting signals**.
 - **Several users can independently use** the same higher bandwidth with very little interference. (e.g. CDMA)

DSSS

- each bit in the original signal is represented by multiple bits in the transmitted signal, using a spreading code
- spreading code spreads the signal across a wider frequency band in direct proportion to the number of bits used

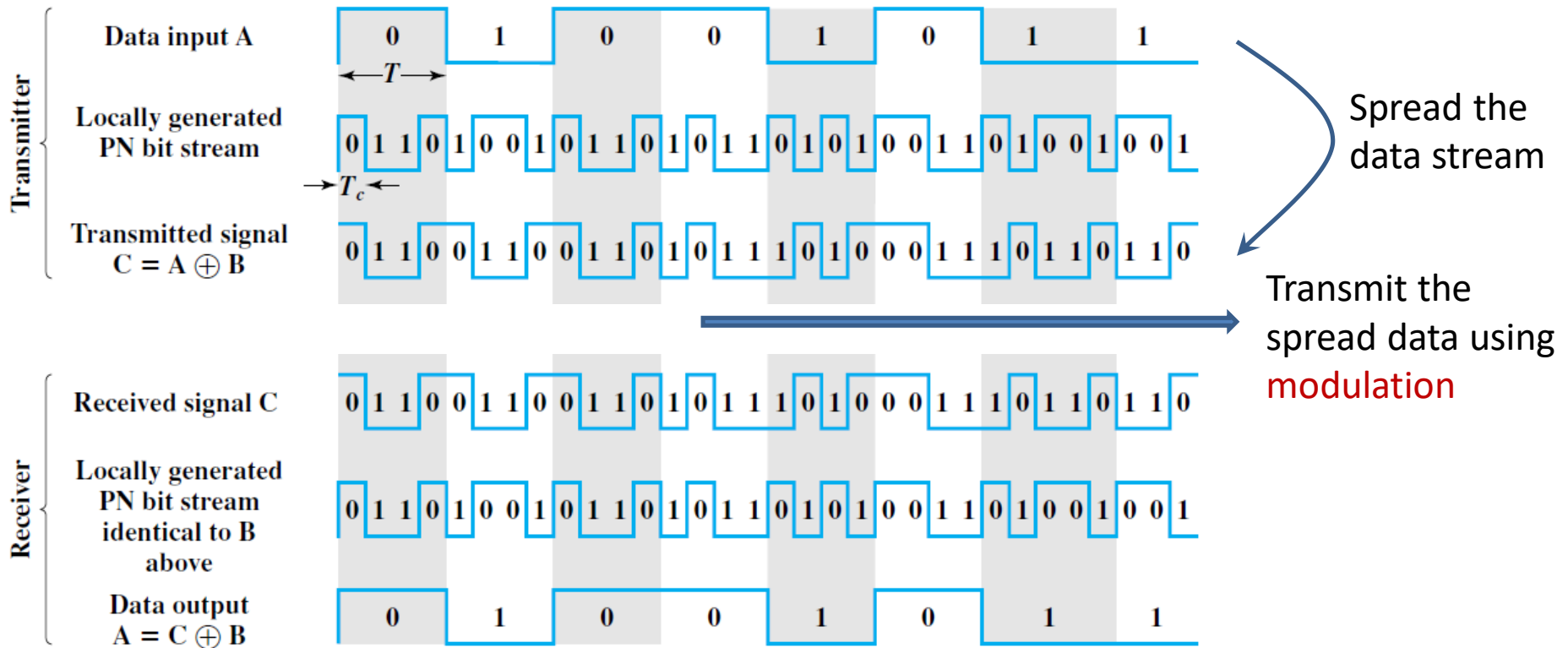
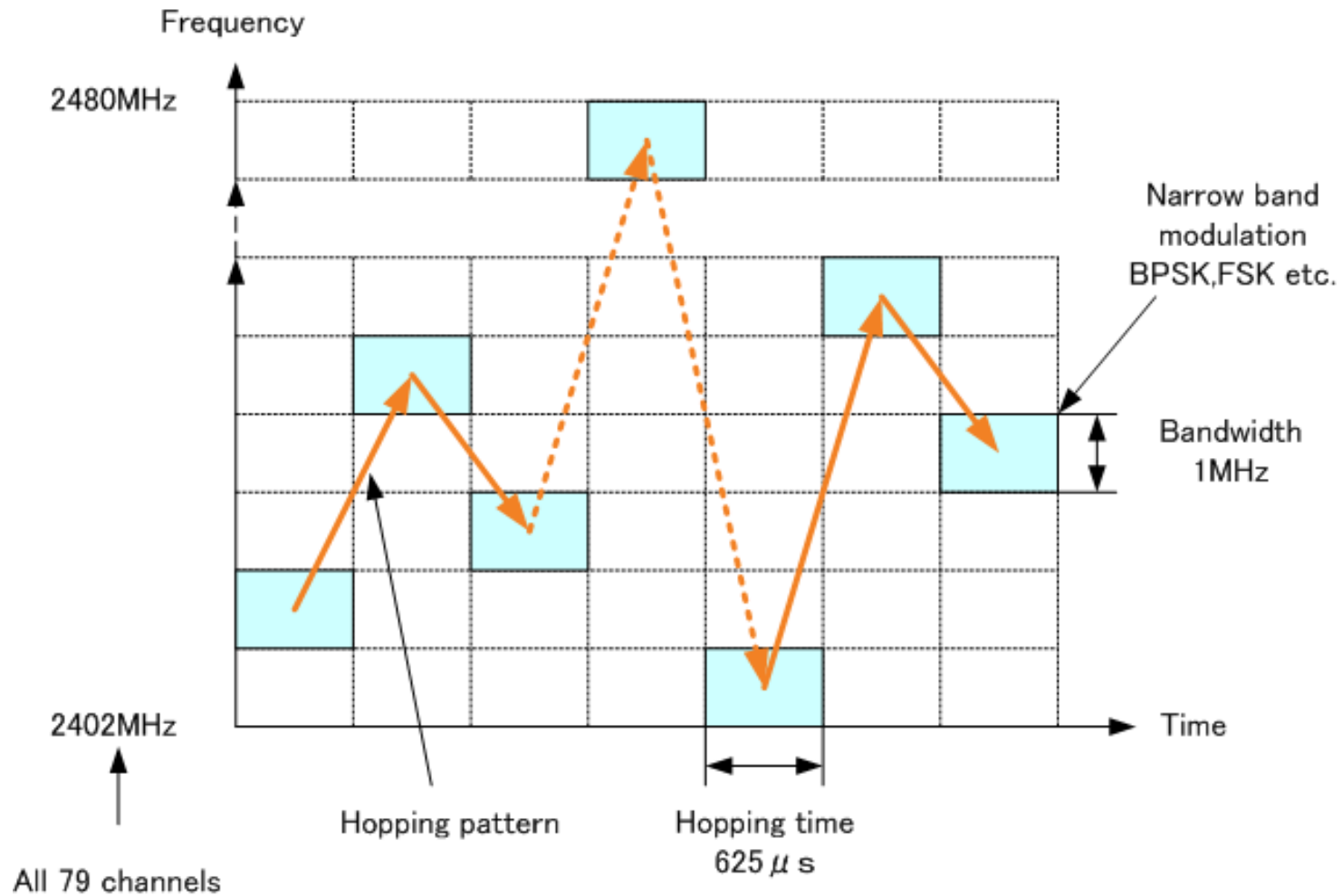
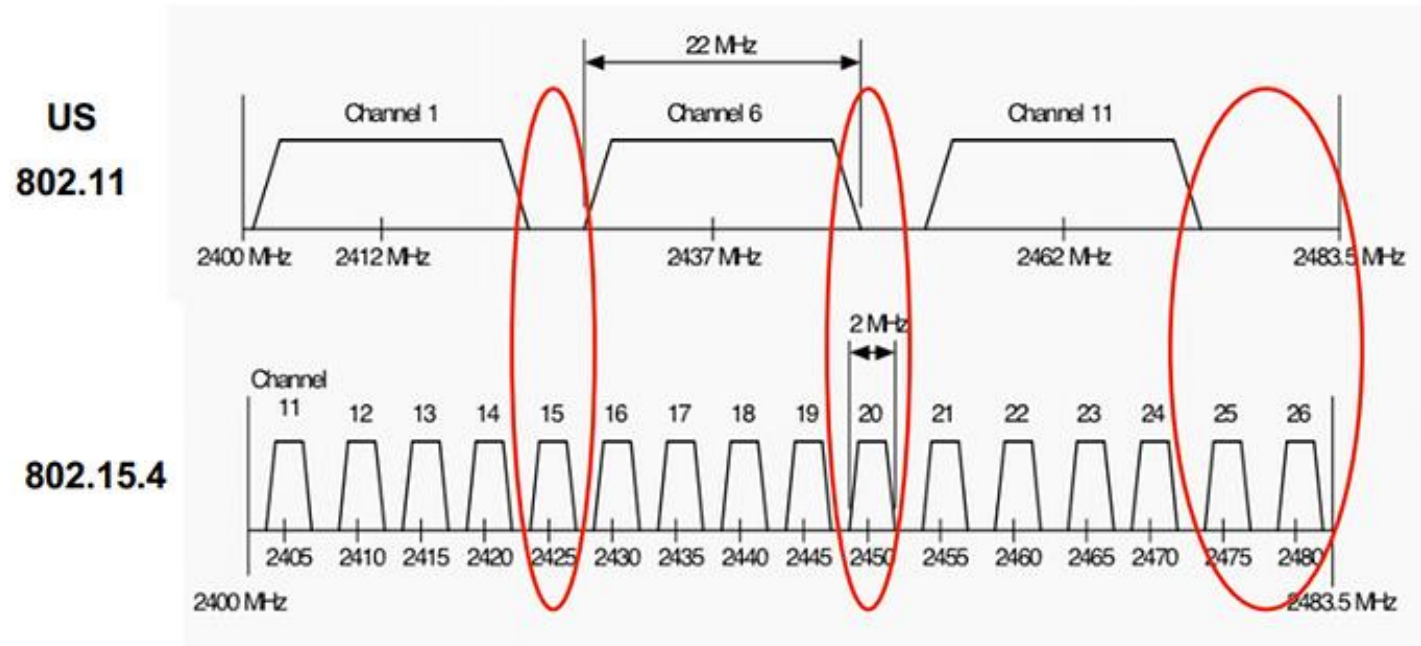


Figure 9.6 Example of Direct Sequence Spread Spectrum

FHSS



Other PHY Attributes



- IEEE 802.15.4 **does not prefer to use frequency hopping** to **minimize energy consumption**.
- To minimize interference in 2.4 GHz band, IEEE 802.15.4 prefer **channel no. 15, 20, 25, 26**
- Transmission power is adjustable from 0.5 mW (min. in 802.15.4) to 1 W (max. in ISM band)
- Transmission power 1 mW provides **theoretical distances** as:
 - Outdoor range **300 m**.
 - Indoor range **100 m**.

Cont...

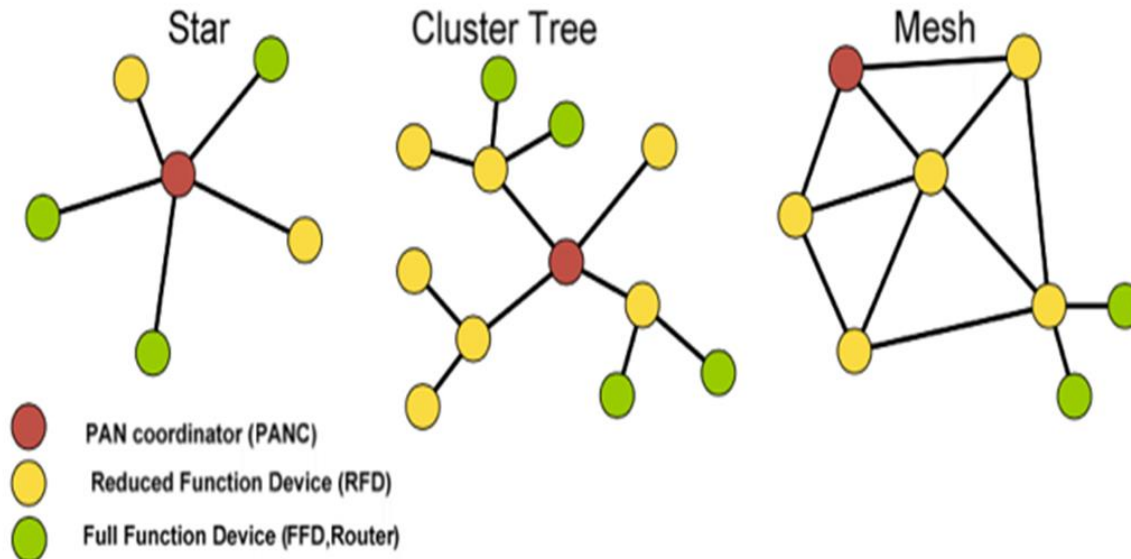


- 802.15.4 **PHY** provides **energy detection (ED)** feature
 - **Application** can request to **asses** each channel's **energy level**
 - It is an estimate of the **received signal power** within the bandwidth of the channel
 - **Coordinator** can make **optimal selection of channel** based on **channels energy level**
- 802.15.4 **PHY** provides **link quality information (LQI)** to **NET and APP layers**
 - The LQI measurement is a characterization of the strength and/or **quality of a received packet**.
 - The measurement may be **implemented using**
 - receiver ED
 - signal-to-noise ratio (SNR) estimation, or
 - combination of the above methods.
 - Transmitter may **decide to use high transmission power** based on LQI
 - Applications may **dynamically change 802.15.4 channels** based on LQI
- 802.15.4 uses **CSMA/CA** which ask the PHY layer to do CCA
 - **Clear Channel Assessment (CCA)** is performed by any one of the below methods:
 - Energy above ED threshold regardless of modulation
 - Carrier sense only (i.e. based on the detection of a signal with modulation and spreading characteristics)
 - Combination of both the above

IEEE 802.15.4 MAC

IEEE 802.15.4 MAC layer

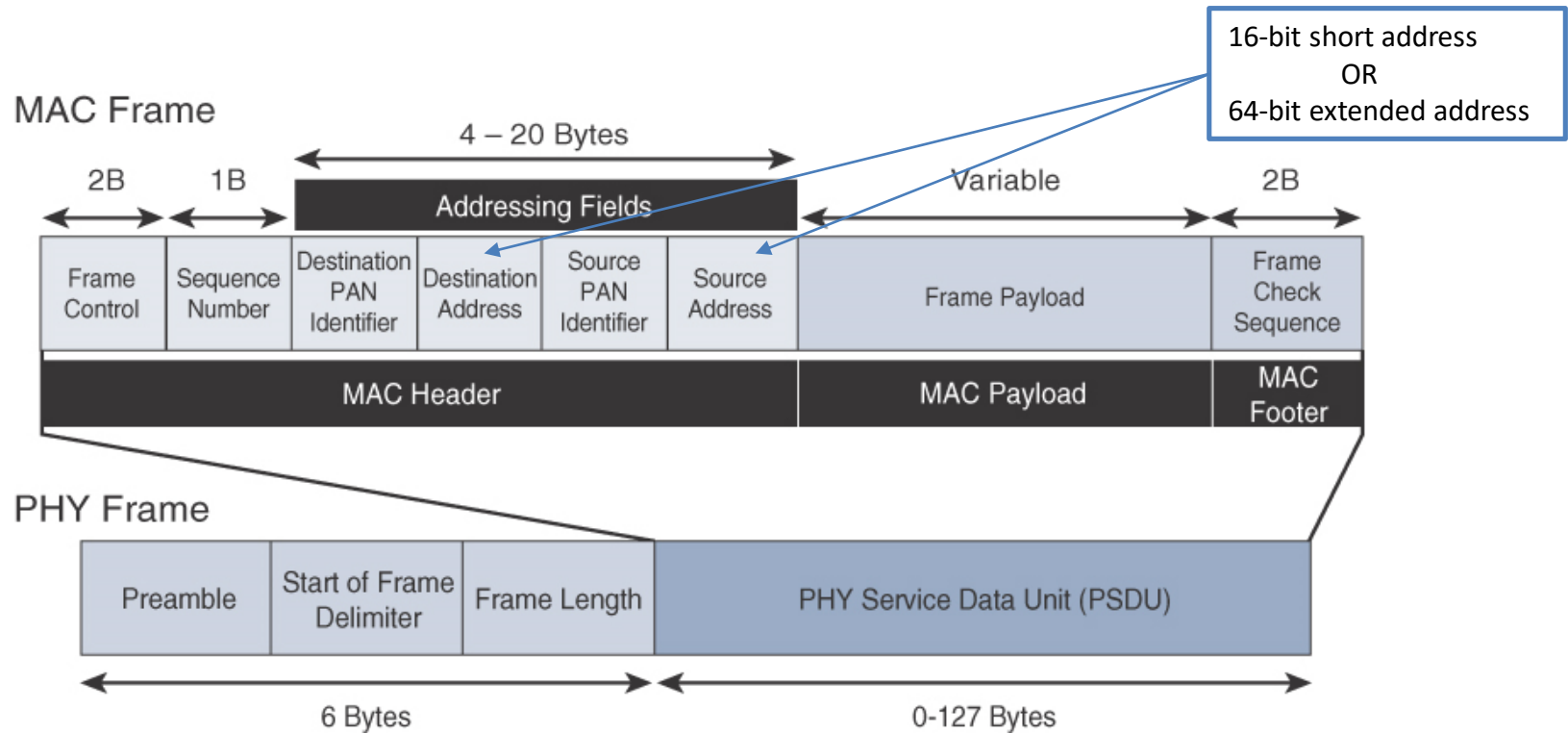
- MAC layer manages access to the PHY channel
 - defines how devices in the same area will share the frequencies allocated.
- **Main tasks:**
 - **Network beaconing** for devices acting as coordinators
 - PAN **association** and **disassociation** by a device
 - **Reliable link communications** between two peer MAC entities
 - Device **security**



IEEE 802.15.4 Device Types

- There are **two different device types** :
 - full function device (**FFD**)
 - reduced function device (**RFD**)
- The **FFD** can operate in **three modes** by serving as
 - **PAN Coordinator**
 - scanning the network and selecting optimal RF channel
 - selecting the 16 bit PAN ID for the network
 - **Coordinator (aka Parent, Join Proxy)**
 - relaying messages to other FFDs including PAN coordinator
 - transmits periodic beacon (under beacon enable access mode)
 - respond to beacon requests
 - **Device**
 - cannot route messages
 - usually receivers are switched off except during transmission
 - attached to the network only as leaf nodes
- The **RFD** can only serve as:
 - **Device**

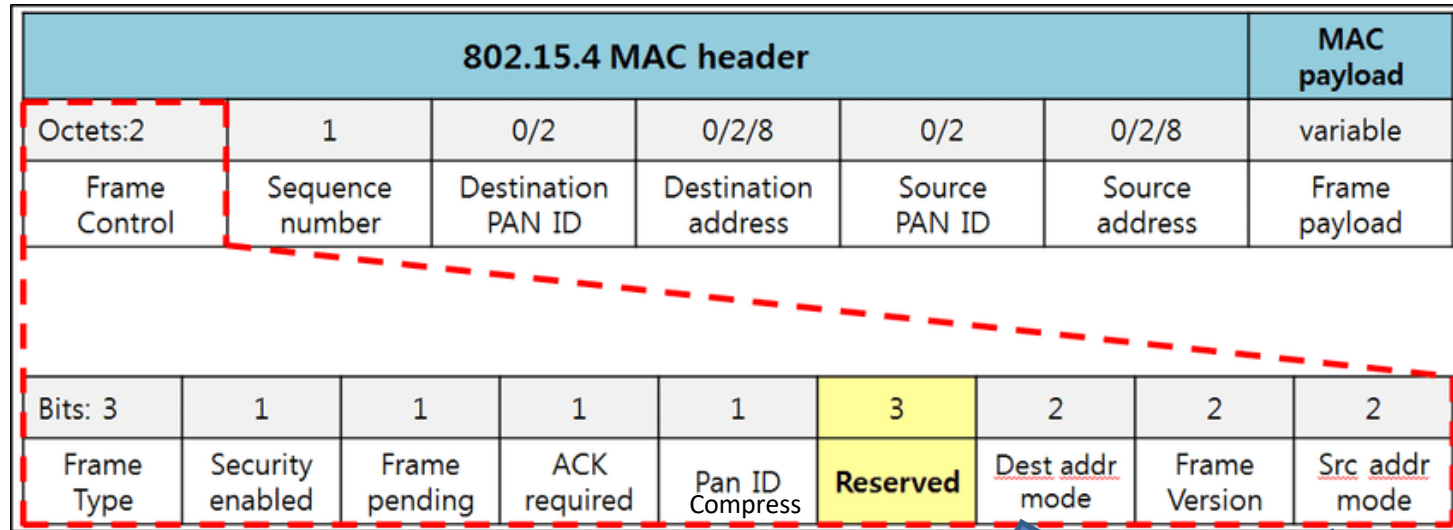
General MAC Frame Format



MAC frame types:

- Data frame
- ACK frame
- Beacon frame
- Command frame

Cont...



-Values of the Frame Type subfield

Frame type value $b_2 b_1 b_0$	Description
000	Beacon
001	Data
010	Acknowledgment
011	MAC command
100-111	Reserved

Addressing mode value $b_1 b_0$	Description
00	PAN identifier and address field are not present.
01	Reserved.
10	Address field contains a 16 bit short address.
11	Address field contains a 64 bit extended address.

Beacon Frame Format

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

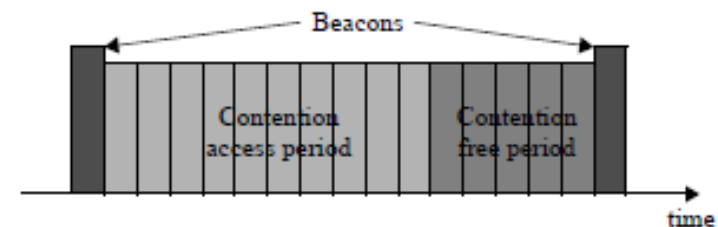
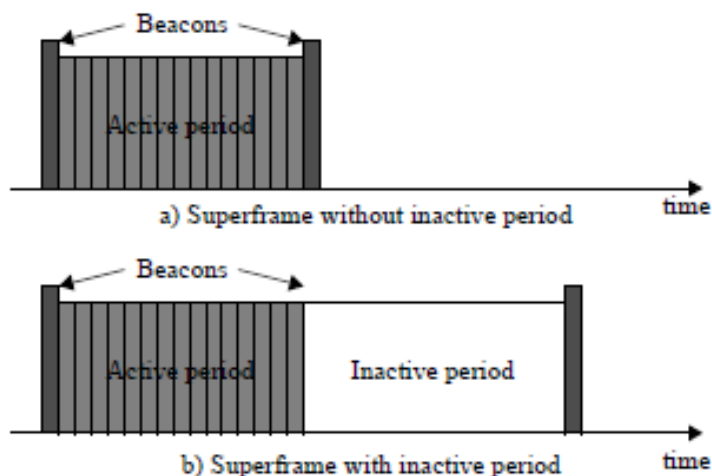


Figure 5-6—Structure of the active periods with GTSS

Beacon Superframe →

Command Frame Format



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

- **Command Frame Types**

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

Data & ACK Frame Format

Data Frame

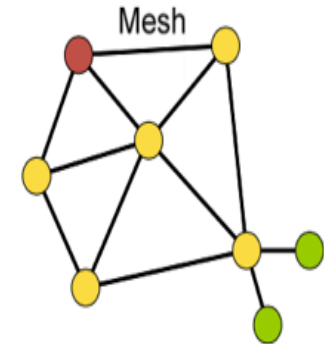
Octets:2	1	4 to 20	variable	2
Frame control	Data sequence number	Address information	Data payload	Frame check sequence
MAC header			MAC Payload	MAC footer

ACK Frame

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

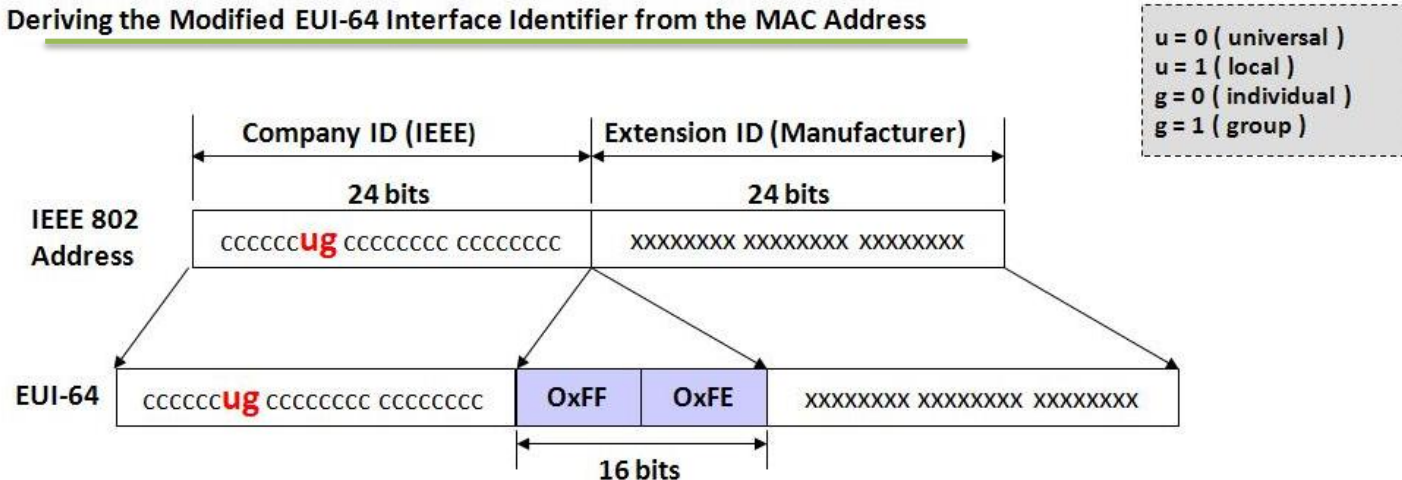
Device Addressing

- Two or more devices communicating on the **same physical channel** constitute a WPAN.
 - A WPAN includes at least one FFD (PAN coordinator)
 - Each independent PAN will select a **unique PAN ID**
- IEEE 802.15.4 devices **can be grouped** into **PAN**. These are identified by their **2 Byte PAN identifier**
- Each device operating on a network has a **unique 64-bit address**
 - called **extended unique identifier (EUI-64)**
 - 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 the device associates with its coordinator.
 - Same short address may be present into different PAN

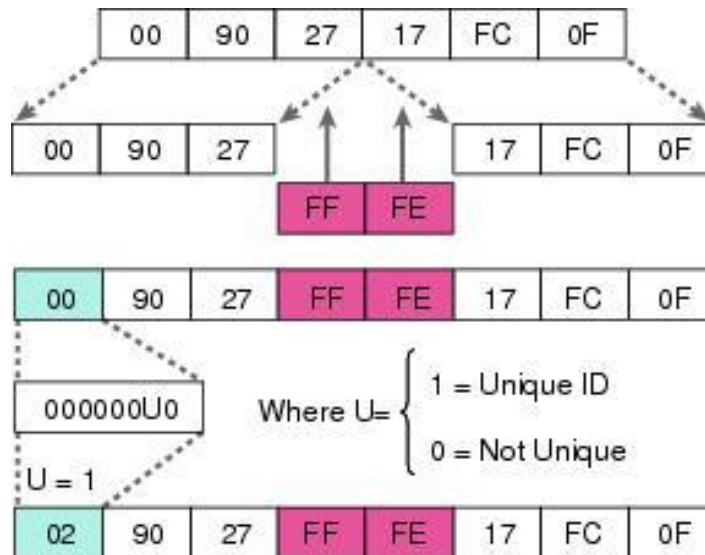


Deriving EUI-64 ID from MAC

Deriving the Modified EUI-64 Interface Identifier from the MAC Address



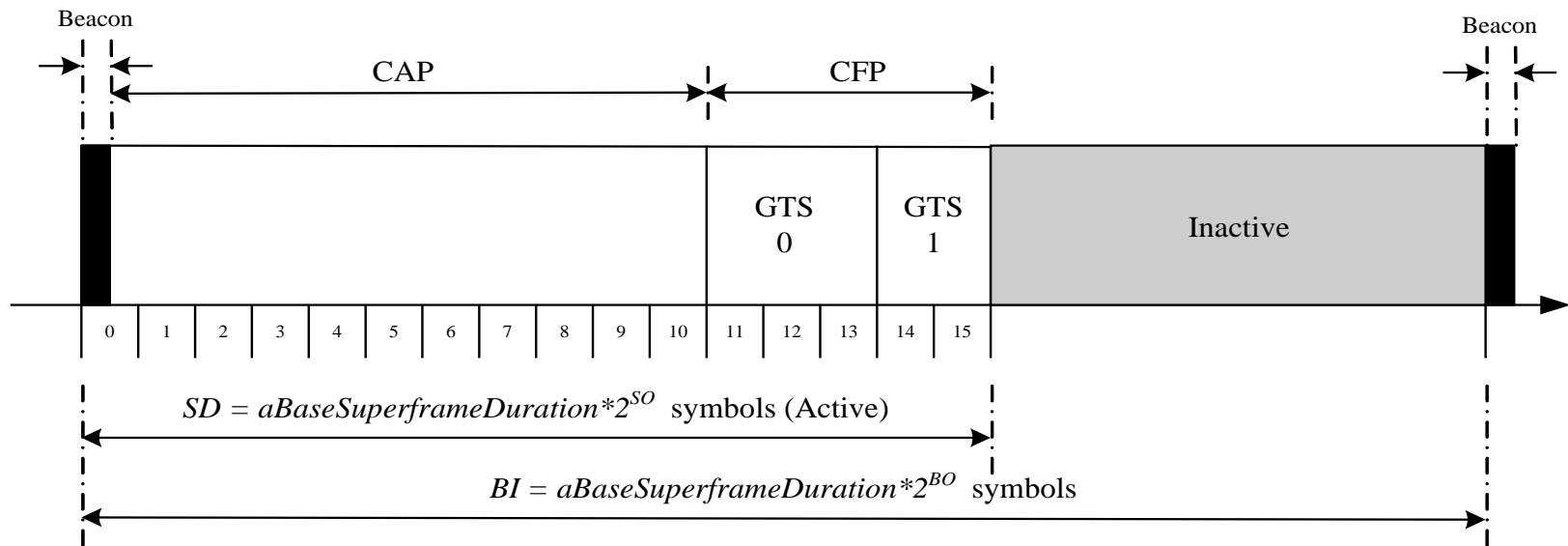
Example:



Addressing Modes

- IEEE 802.15.4 frames contain **address of both the source & destination**.
- **Three different addressing modes**, which sets the address field (none/short/long, with/without PAN ID)
 - **Short addressing mode**: The address field includes a short address (2B) & a PAN ID (2B) = (total of 4 bytes).
 - **Long addressing mode**: The address field includes a long address (8B) and a PAN ID (2B) = (total of 10 bytes).
 - **No addressing mode**:
 - For ACK frame - both addresses are missing.
 - For *Data* and *Command* frames - **only one** (either source or destination) field **can be omitted**
 - if the **source address is omitted**, it means the PAN coordinator sent the frame;
 - if the **destination address is missing**, it means it should be received by the PAN coordinator.

Superframe



- A superframe is divided into **two parts**

- **Inactive:** all station sleep.
 - no communication
 - nodes can turn their **radios off** and go into power saving mode
- **Active:**
 - Active period is divided into **16 slots** in general
 - 16 slots are further divided into two parts
 - Contention access period (**CAP**)
 - Contention free period (**CFP**)
 - Beacon only period (**BOP**)

- **superframe order (SO)** : decides the length of the active portion in a superframe
- **beacon order (BO)** : decides the length of a superframe or beacon transmission period
- **beacon-enabled** network should satisfy $0 \leq SO \leq BO \leq 14$
- **PAN coordinator decides SO, BO**
 - Default value: SO=3, BO=5
- SD: Superframe Duration
- BI: Beacon Interval

Cont...

- *aBaseSlotDuration*
= The number of symbols forming a superframe slot when *the superframe order (SO)* is equal to zero
= 60 PHY symbols
- *aNumSuperframeSlots*
= The number of slots contained in any superframe
= 16
- *aBaseSuperframeDuration*
= The number of symbols forming a superframe when *the superframe order (SO)* is equal to zero
= *aBaseSlotDuration* × *aNumSuperframeSlots*
- So, Length of a superframe
= can range from 15.36 msec to 215.7 sec (= 3.5 min).
- Each device will be
 - active for $2^{-(BO-SO)}$ portion of the time
 - 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

Beaconed / Non-beaconed network

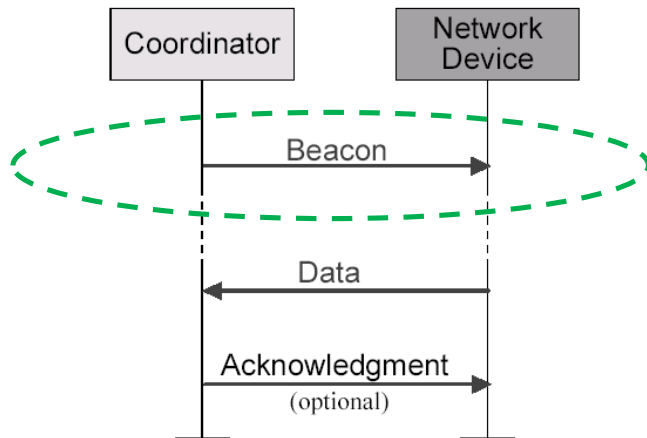
- In a “beacon-enabled” network (**i.e. uses superframe structure**)
 - Devices use the **slotted CAMA/CA** mechanism to contend for the channels
 - FFDs who require **fixed rates of transmissions** can ask for **GTS** from the coordinator
- In a “nonbeacon-enabled” network (**i.e. do not use superframe structure**)
 - Devices use the **unslotted CAMA/CA** mechanism for channel access
 - **GTS** shall not be permitted
- CSMA/CA is **not used for Beacon** transmission;
- CSMA/CA is also **not used** for **Data** transmission **during CFP**
- **Beacons** are used for
 - ❖ announcing the existence of a PAN
 - ❖ synchronizing with other devices
 - ❖ informing pending data in coordinators
 - ❖ starting superframes

Data Transfer: Device -> Coordinator



In a beacon-enabled network

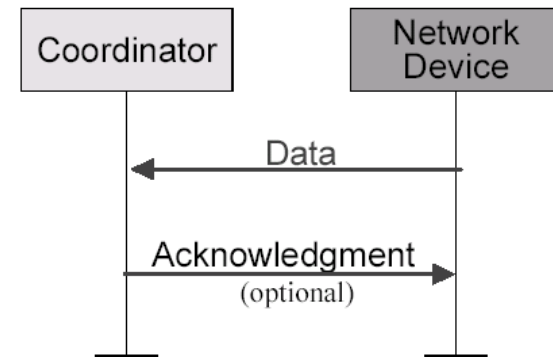
- a device finds the beacon to **synchronize** to the **superframe** structure.
- Then it uses **slotted CSMA/CA** to transmit its data.



Communication to a coordinator
In a **beacon-enabled** network

In a non-beacon-enabled network

- device simply transmits its data using **unslotted CSMA/CA**

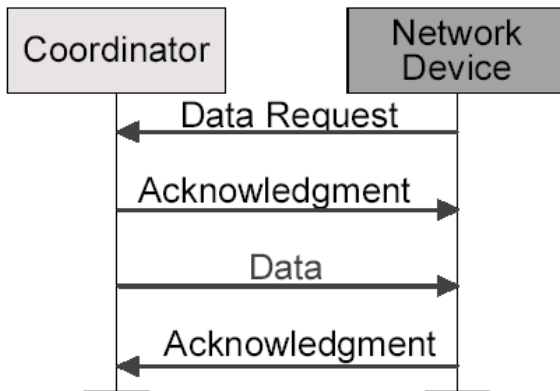
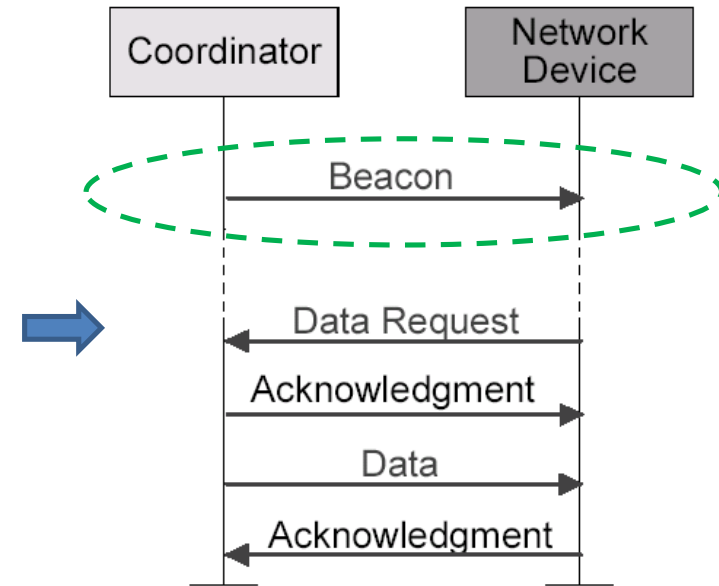


Communication to a coordinator
In a **non-beacon-enabled** network

Data Transfer: Coordinator -> Device

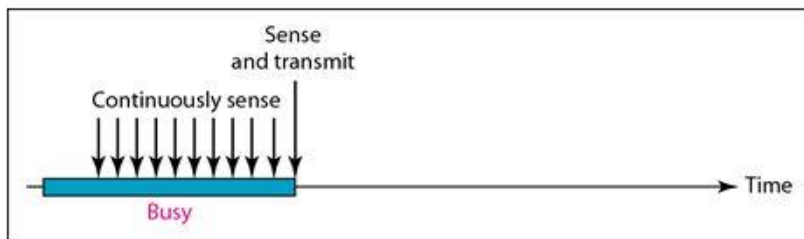


- Data transferred **from coordinator to device**
 - in a **beacon-enabled** network:
 - The **coordinator indicates** in the **beacon** that some data is pending.
 - A device periodically listens to the beacon and transmits a **Data Request** command using **slotted CSMA/CA**.
 - Then **ACK, Data, and ACK**

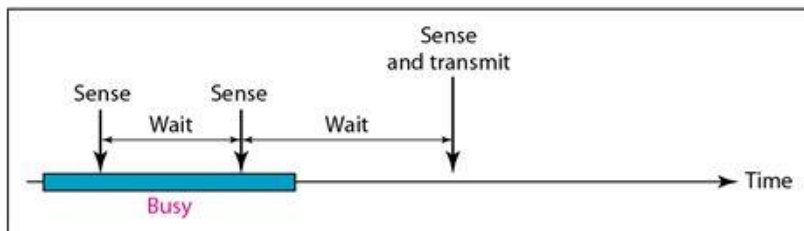


- Data transferred **from coordinator to device**
 - in a **non-beacon-enabled** network:
 - The device transmits a **Data Request** using **unslotted CSMA/CA**.
 - If the coordinator has its pending data, an **ACK** is replied.
 - Then the coordinator transmits **Data** using **unslotted CSMA/CA**.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

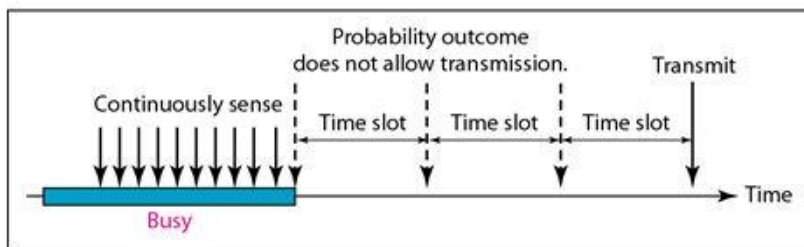
Channel Access Mechanism



a. 1-persistent



b. Nonpersistent



c. p-persistent

- **CSMA** requires that each station **first check the state of the medium** before sending.
- This method aims to **decrease the chances of collisions** when two or more stations want to transmit data
- **Persistent** methods can be applied to take action when the channel is sensed busy/idle.
 - **1-persistent**
 - When station found idle channel, it **transmits the frame without any delay**.
 - **Non-persistent**
 - when the channel is found busy, it will **wait for the random time** and again sense for the state of the station whether idle or busy
 - **p-persistent**
 - If the channel found to be idle, it **transmits the frame with probability p**
 - This is implemented using **backoff period** concept

Unslotted CSMA/CA

- CSMA/CA random channel access

- nonbeacon-enabled network → uses **unslotted CSMA/CA**

In unslotted CSMA/CA:

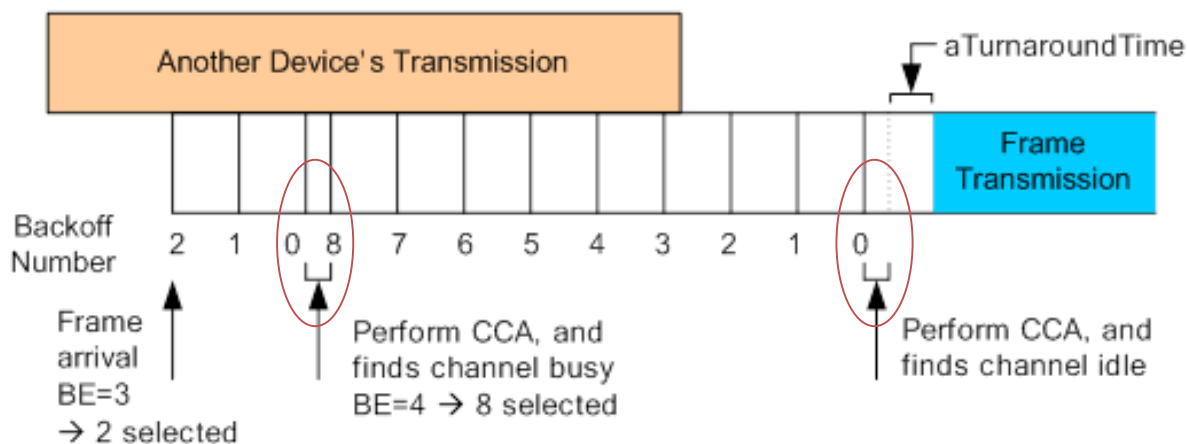
- The **backoff periods** of one device **are not related in time** to the backoff periods of any other device in the PAN.
- One backoff period = *aUnitBackoffPeriod*.

Backoff:

- is an algorithm that uses feedback to **multiplicatively decrease the rate** of some process

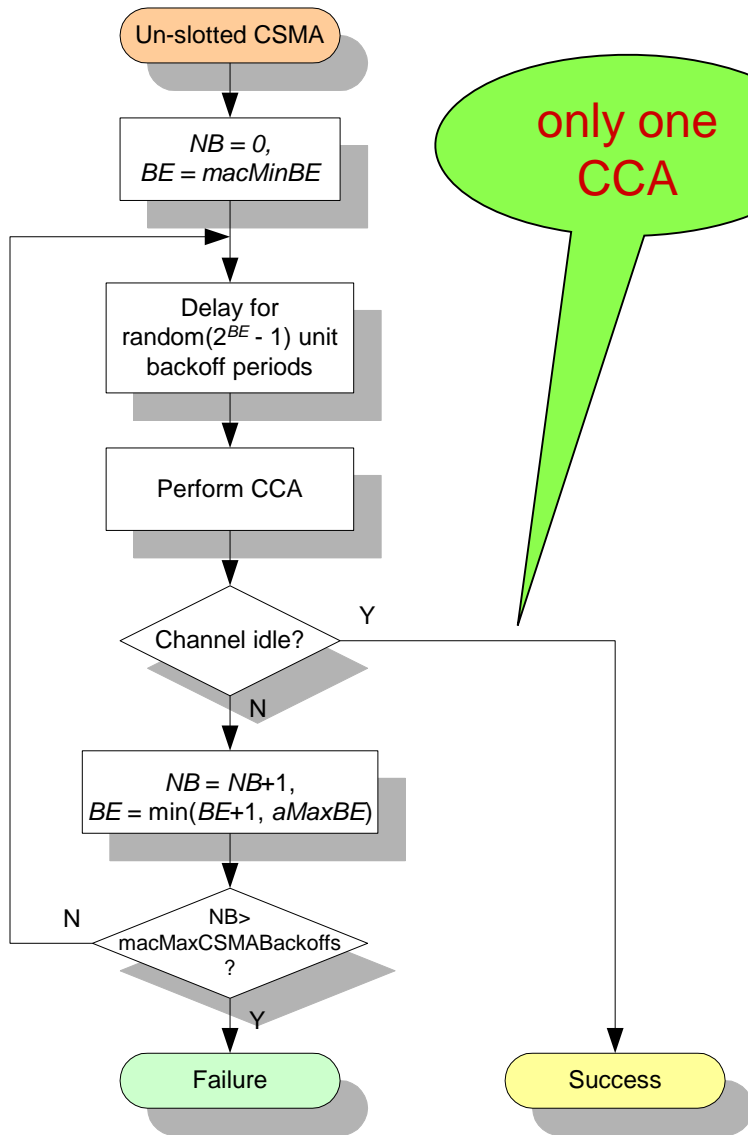
Binary exponential backoff (BEB)

- After **c collisions** in BEB algo., the delay is **randomly chosen** from $[0, 1, \dots, N]$ slots, where $N = 2^c - 1$.



BE: Backoff Exponent

Cont...



NB (Number of Backoff): number of times that backoff has been taken in this attempt of transmission

- if exceeding macMaxCSMABackoff , the attempt fails

BE (Backoff Exponent): play the role to decide how many backoff periods a device shall wait before attempting to assess a channel.

CCA (Clear Channel Assessment)

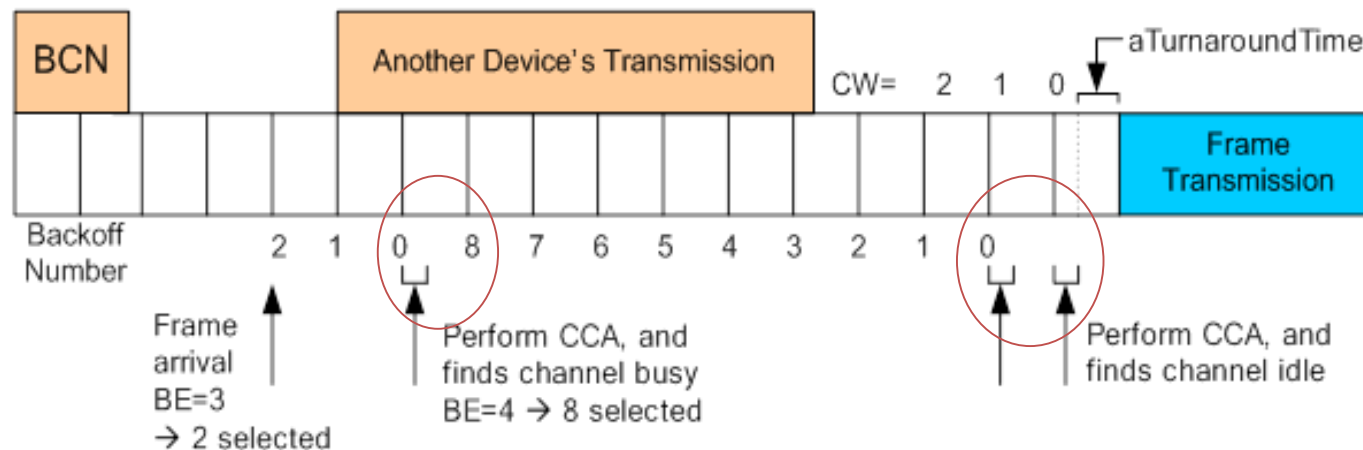
Slotted CSMA/CA

- CSMA/CA random channel access

- beacon-enabled network → uses **slotted CSMA/CA**

In slotted CSMA/CA:

- 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**

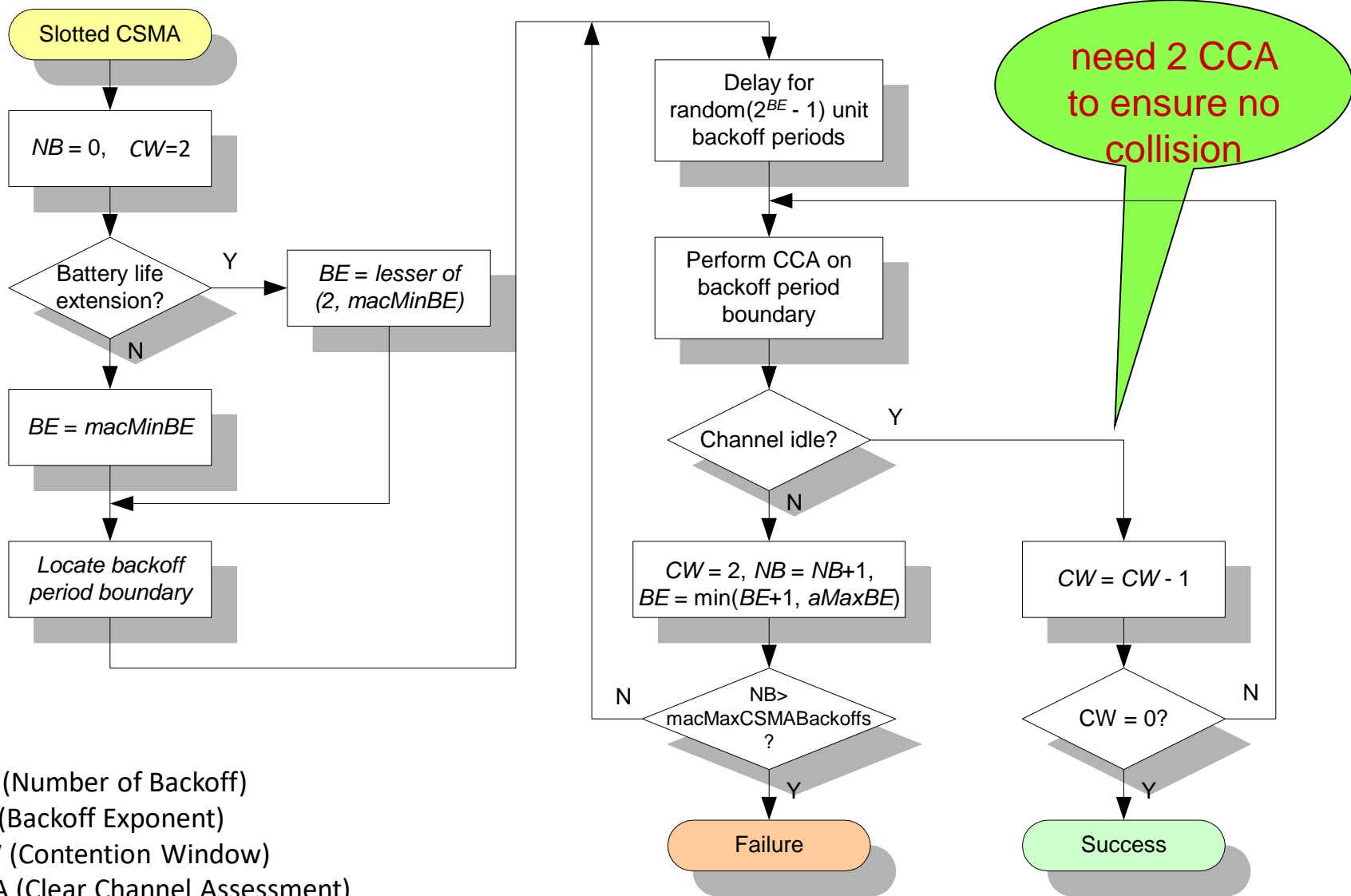


Cont...



- Each device maintains 3 variables for each transmission attempt
 - **NB (Number of Backoff)**: number of times that backoff has been taken in this attempt of transmission
 - if exceeding `macMaxCSMABackoff`, the attempt fails
 - **BE (Backoff Exponent)**: play the role to decide **how many backoff periods** a device shall wait before attempting to assess a channel.
 - The number of **backoff periods** is **lesser than** the remaining number of slots in the CAP
 - Otherwise, MAC sublayer shall **pause the backoff countdown at the end of the CAP**, and resume it at the start of the CAP in the next superframe
 - **CW (Contention Window)**: 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.
 - **Note**: CW in 802.15.4 is not same with CW in 802.11
 - CW in 802.11 is used to decide the backoff window size from which the backoff period is chosen randomly
 - CW in 802.15.4 is used to decide how many rounds of CCA is required before getting the channel access
- **Battery Life Extension (BLE)**:
 - designed for very low-power operation, where **a node only contends in the first few slots**

Cont...



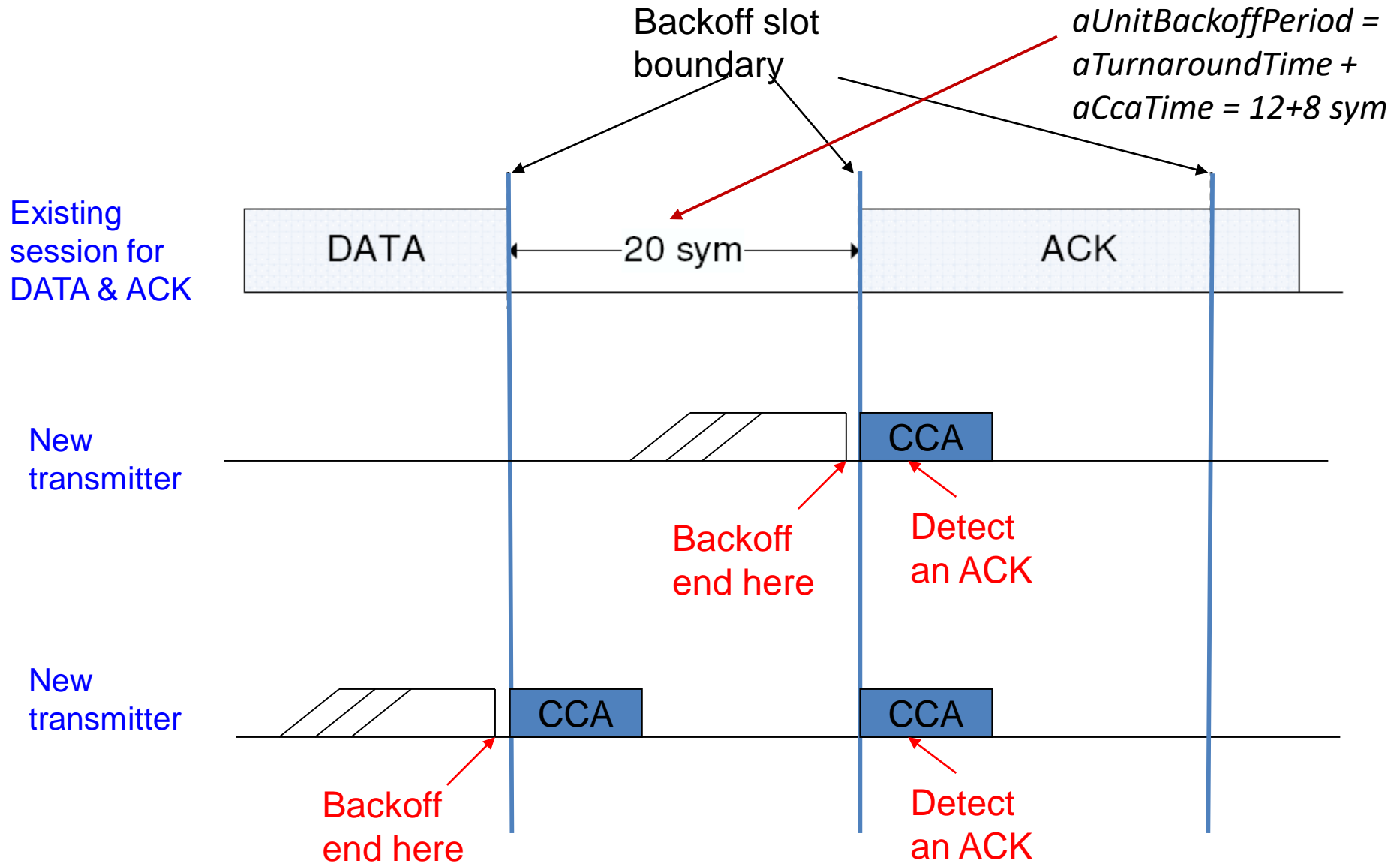
NB (Number of Backoff)
BE (Backoff Exponent)
CW (Contention Window)
CCA (Clear Channel Assessment)

Why 2 CCAs to Ensure Collision-Free

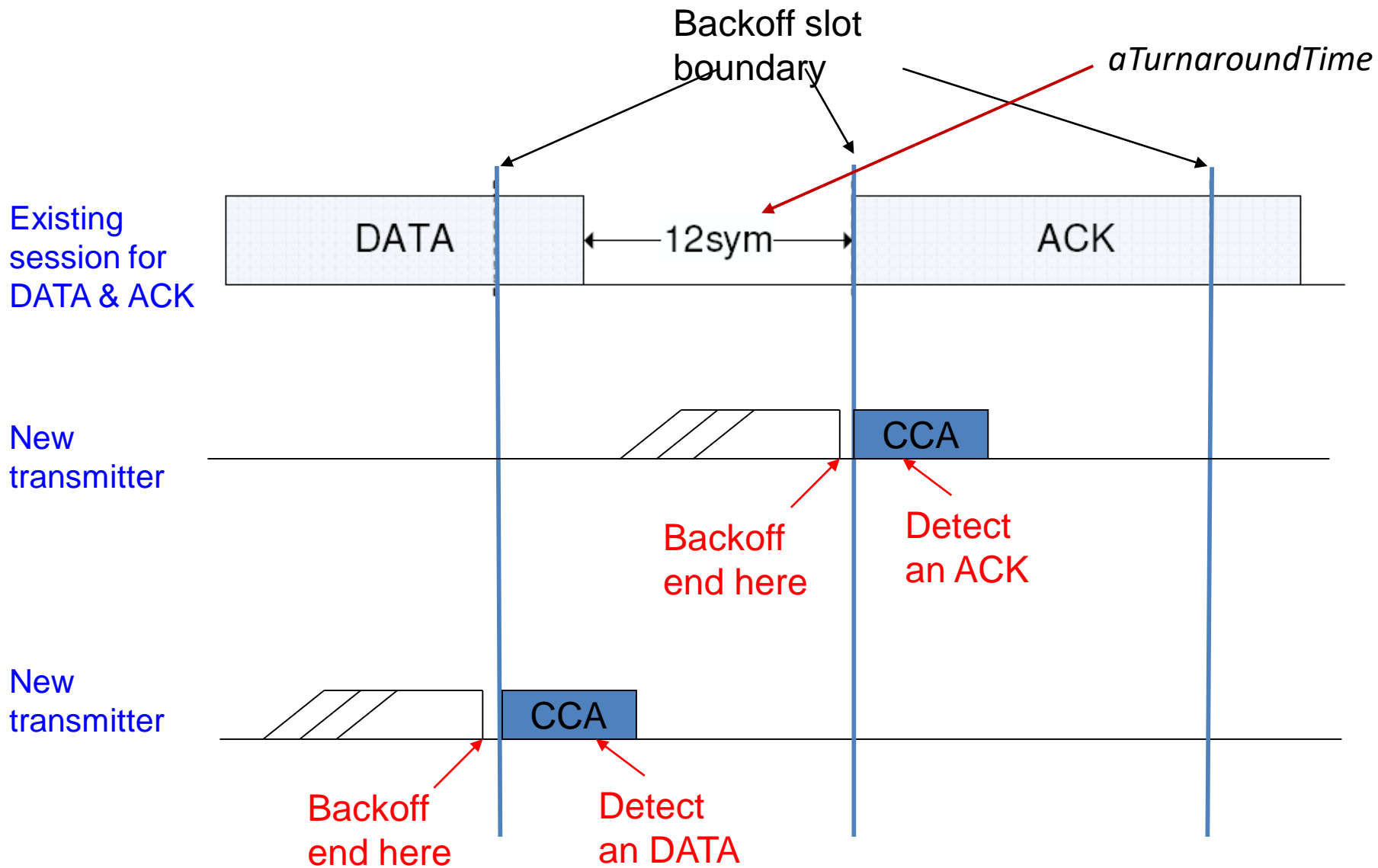


- Each CCA occurs at the boundary of a **backoff slot**
- Each **Backoff Slot duration** = 20 PHY symbols
- Each **CCA duration** = 8 PHY symbols
- The standard specifies that a **transmitter node performs the CCA twice in order to protect acknowledgment (ACK)**.
 - When an ACK packet is expected, the 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)

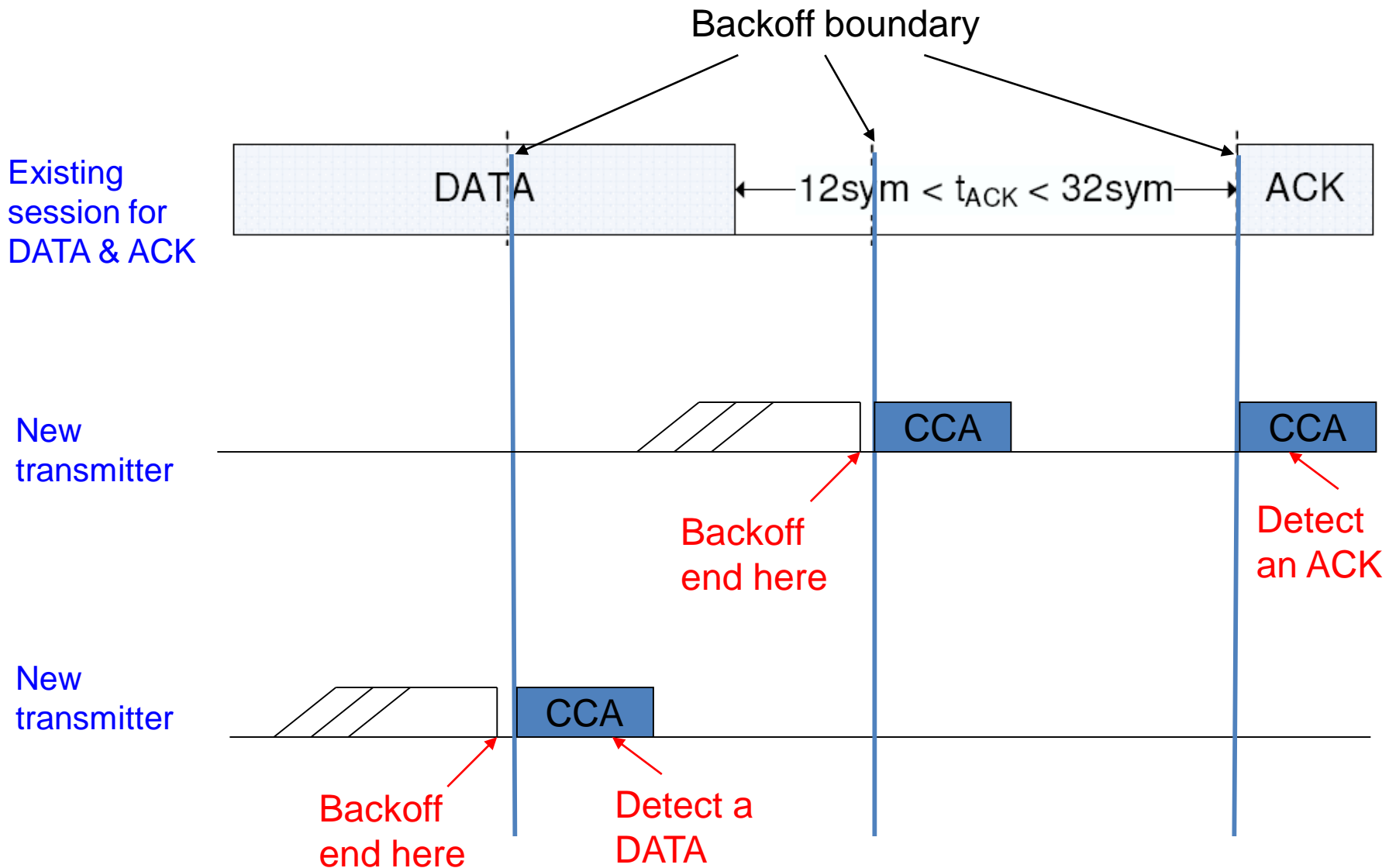
Why 2 CCAs (case 1)



Why 2 CCAs (Case 2)



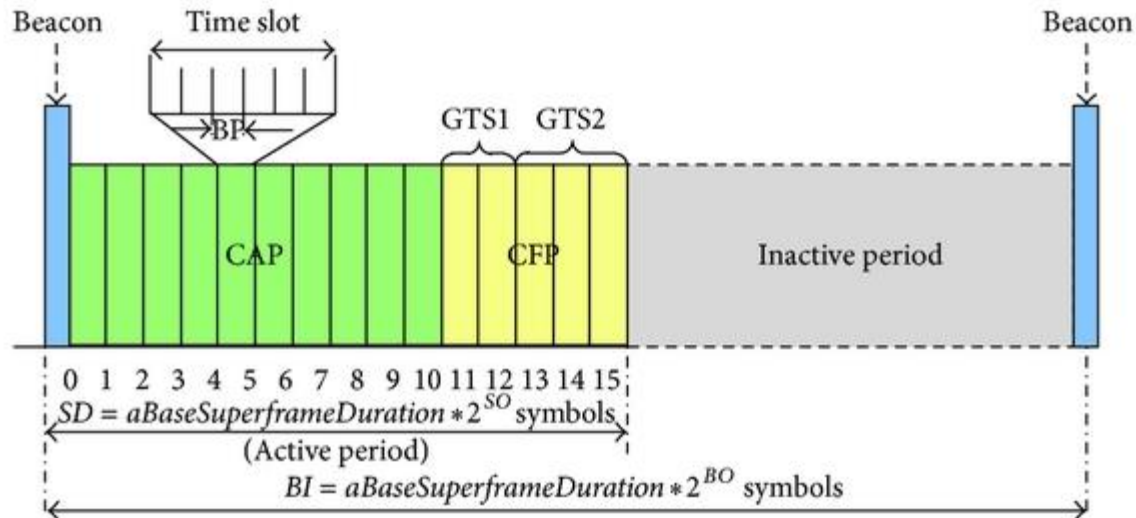
Why 2 CCAs (Case 3)



GTS Concepts



- 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 allocate 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

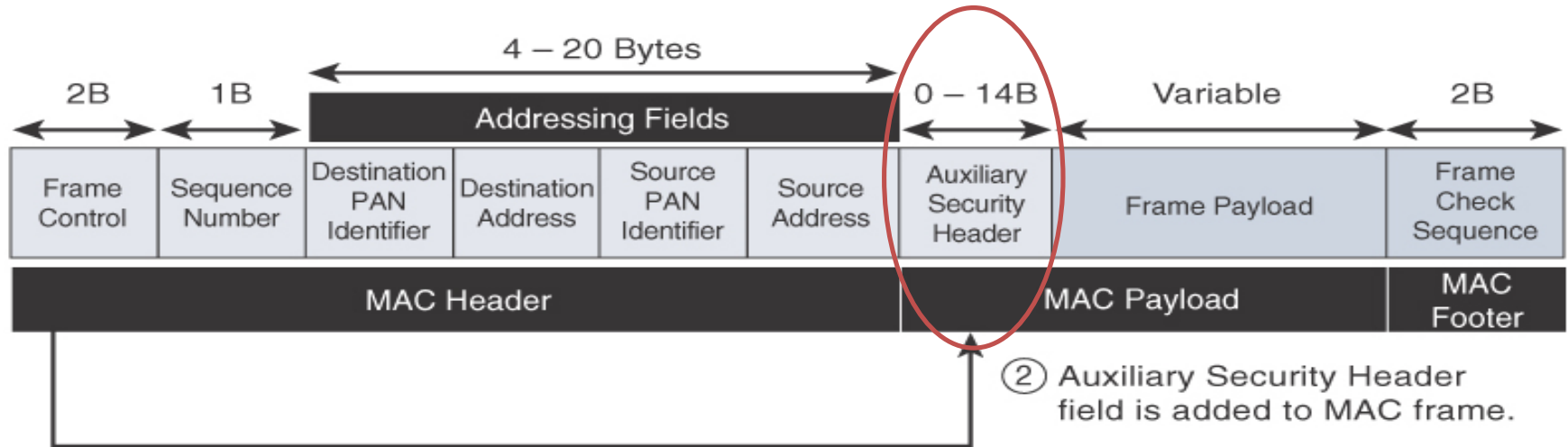


Cont...



- 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**
- Before GTS starts, the **GTS direction** shall be specified as either Tx or Rx
 - 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 by an RFD is optional

Security



① Security Enabled bit in Frame Control is set to 1.

- IEEE 802.15.4 specification uses **Advanced Encryption Standard (AES)** with a 128-bit key length as the base encryption algorithm
- **Message integrity code (MIC)**, which is calculated for the entire frame using the same AES key, to validate the data that is sent

Limitations in 802.15.4



- **Disadvantages of Initial version of IEEE 802.15.4**

- MAC reliability
- unbounded latency
- multipath fading

- **IEEE 802.15.4e** amendment of IEEE 802.15.4-2011 expands the MAC layer feature set

- to remedy the disadvantages of 802.15.4.
- to better suitable in factory and process automation, and smart grid
- **Main modifications** were:
 - frame format,
 - security,
 - determinism mechanism,
 - frequency hopping

- **IEEE 802.15.4g** amendment of IEEE 802.15.4-2011 expands the PHY layer feature set

- to optimize large outdoor wireless mesh networks for field area networks (FANs)
- to better suitable in smart grid or smart utility network (SUN) communication
- **Main modifications** were:
 - New PHY definitions
 - some MAC modifications were needed to support the new PHY

Lessons Learned



- ✓ What is IEEE 802.15.4

- ✓ IEEE 802.15.4. PHY
 - Functionalities
 - Modulation, QPSK, OQPSK
 - Spread Spectrum, DSSS, FHSS

- ✓ IEEE 802.15.4 MAC
 - MAC Frame Formats
 - Timeslot, Superframe
 - Device Addressing
 - Data Transfer Model
 - Channel Access Methods
 - Guaranteed time slot (GTS)
 - Association Procedure
 - Security

- ✓ Limitations of IEEE 802.15.4

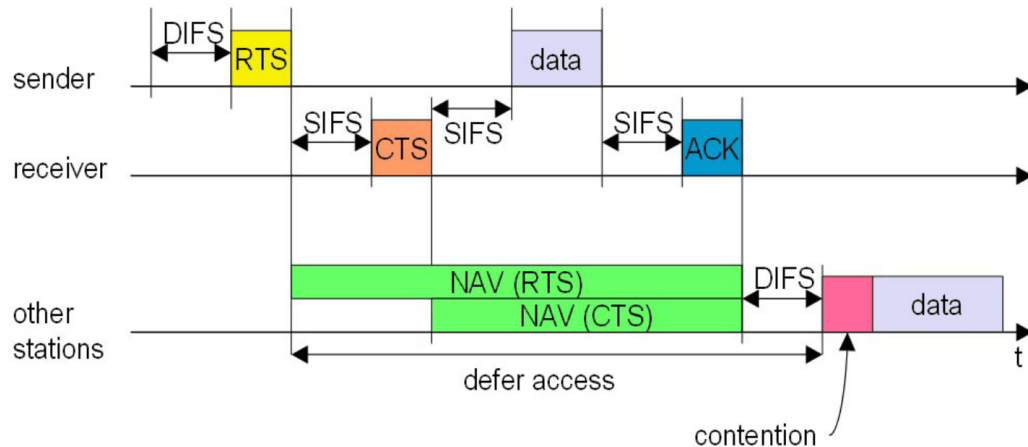
Thanks!



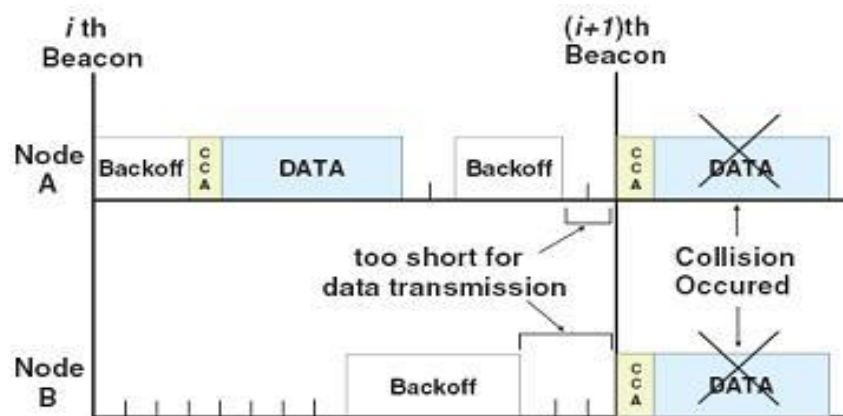
Figures and slide materials are taken from the following sources:

1. David Hanes *et al.*, “IoT Fundamentals: Networking Technologies, Protocols, and Use Cases for the Internet of Things”, 1st Edition, 2018, Pearson India.
2. Oliver Hersent et al., “The Internet of Things: Key Applications and Protocols”, 2018, Wiley India Pvt. Ltd.

Contention in 802.11 & 802.15.4



Contention in IEEE 802.11 DCF



Contention in IEEE 802.15.4 (for slotted CSMA/CA)