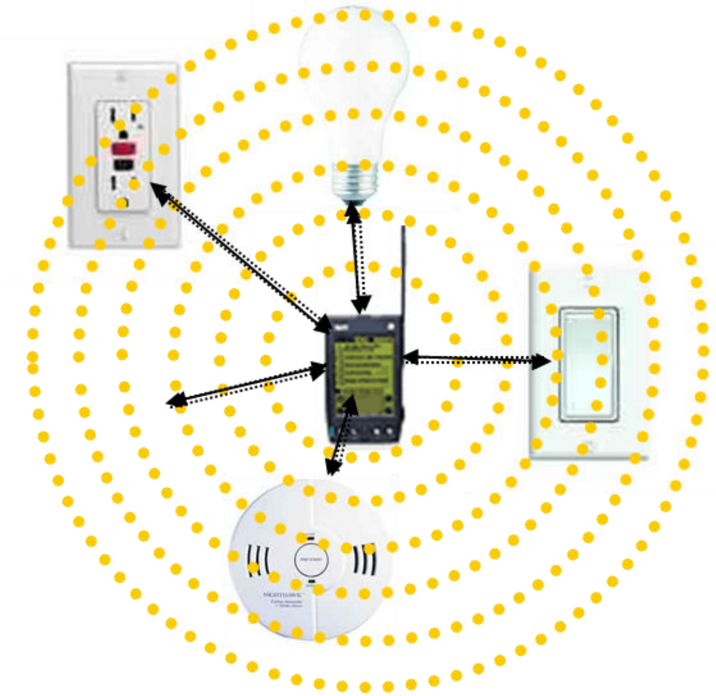
IEEE 802.15.4 MAC Mechanism

IEEE 802.15.4 Applications

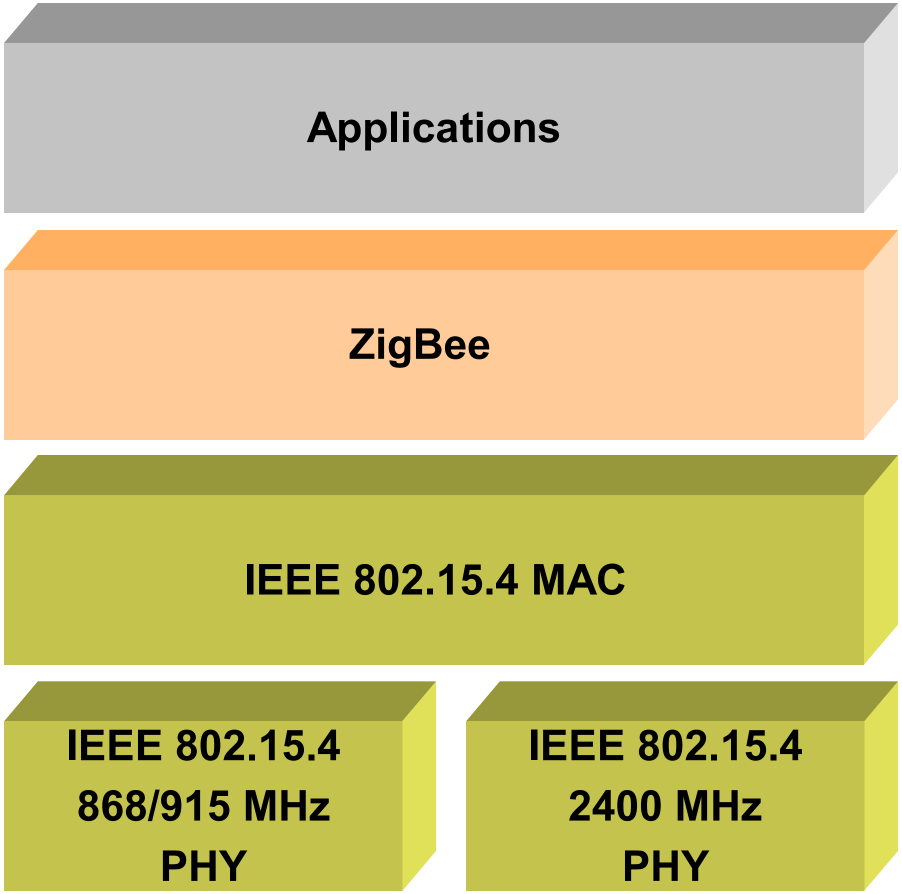
- **Home Networking**
- **Automotive Networks**
- **Industrial Networks**
- **Interactive Toys**
- **Remote Metering**



IEEE 802.15.4 General Characteristics

- **Data rates of 250 kb/s, 40 kb/s and 20 kb/s.**
- **Star or Peer-to-Peer operation.**
- **Support for low latency devices.**
- **Fully hand-shaked protocol for transfer reliability.**
- **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 / ZigBee Architecture



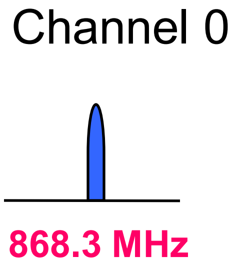
- Network Routing
- Address translation
- Packet Segmentation
- Profiles

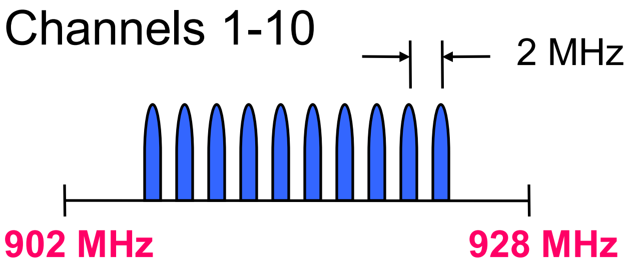
- Channel acquisition
- Contention mgt
- NIC address
- Error Correction

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

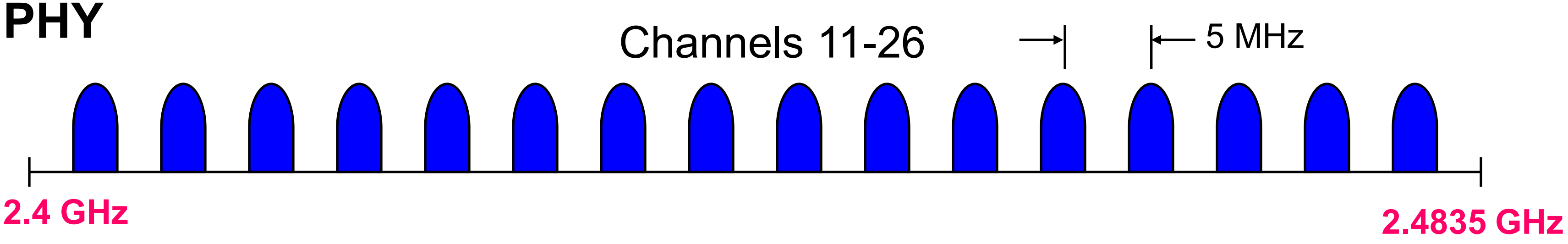
Operating Frequency Bands: PHY Layer overview

868MHz / 915MHz
PHY





2.4 GHz
PHY



Operating Frequency Bands: PHY Layer 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

Operating Frequency Bands: PHY Layer overview

- **Transmit Power**
- Capable of at least .5 mW

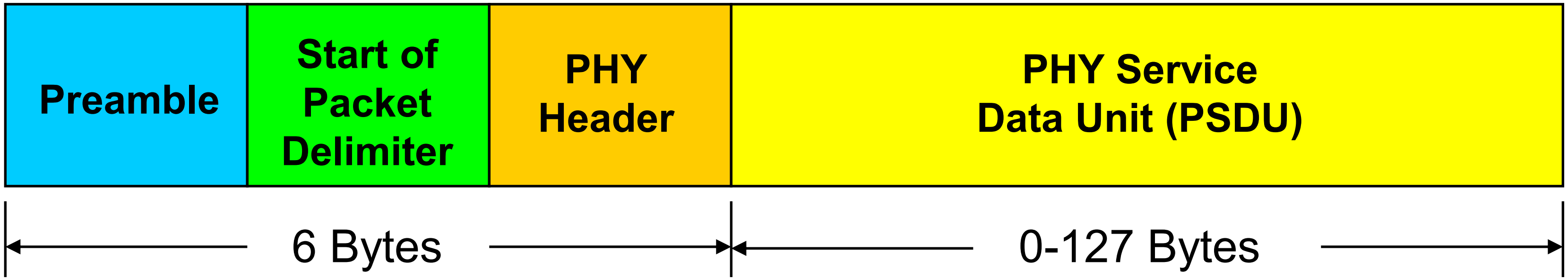
- **Transmit Center Frequency Tolerance**
- ± 40 ppm

- **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

Packet Structure

- **PHY Packet Fields**
- Preamble (32 bits): synchronization
- Start of Packet Delimiter (8 bits)
- PHY Header (8 bits): PSDU length
- PSDU (0 to 1016 bits): Data field



Preamble

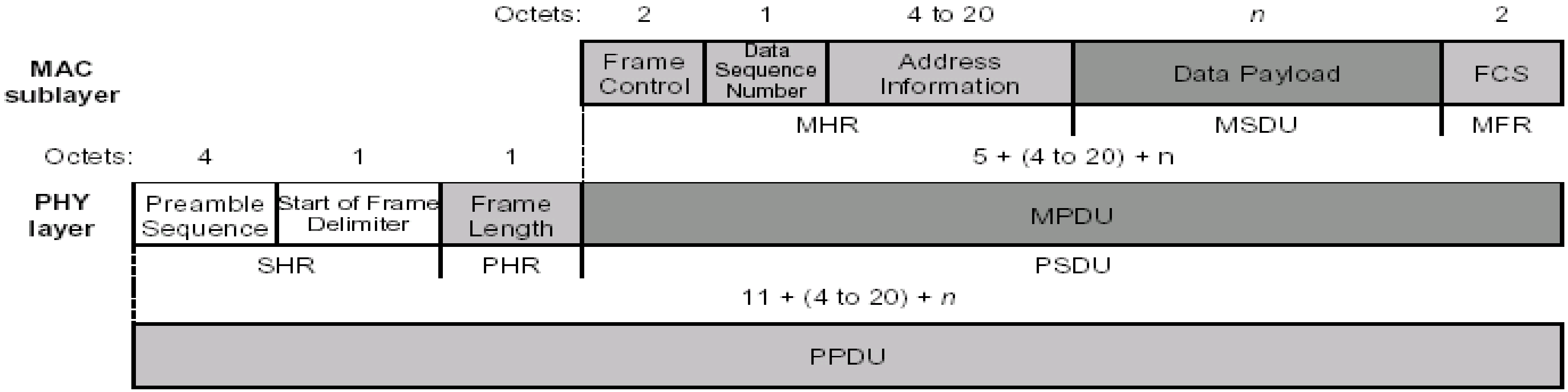
Start of Packet Delimiter

PHY Header

PHY Service Data Unit (PSDU)

6 Bytes

0-127 Bytes



Device Classes

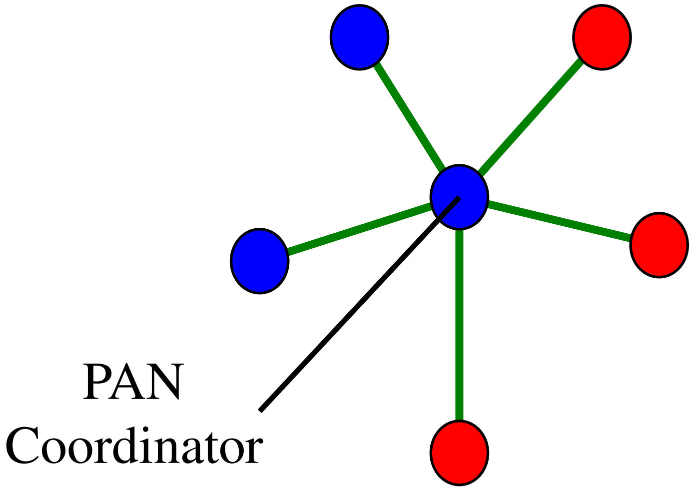
- Full function device (FFD)
  - Any topology
  - Network coordinator capable
  - Talks to any other device

- Reduced function device (RFD)
  - Limited to star topology
  - Cannot become a network coordinator
  - Talks only to a network coordinator
  - Very simple implementation

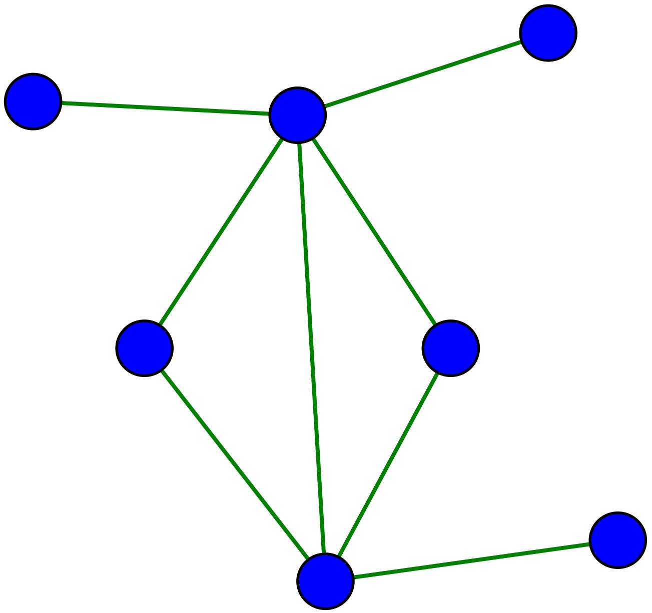
Types of Nodes

- **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**.

Typical Network Topologies



Star topology

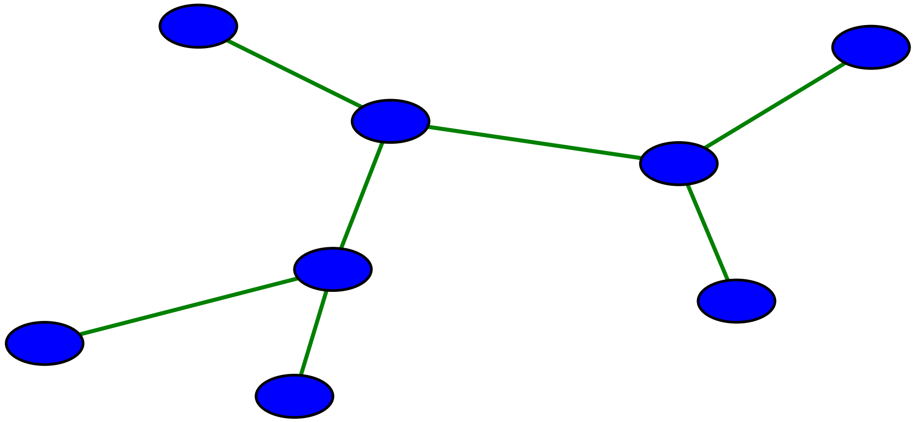


Point to point

— Communications flow

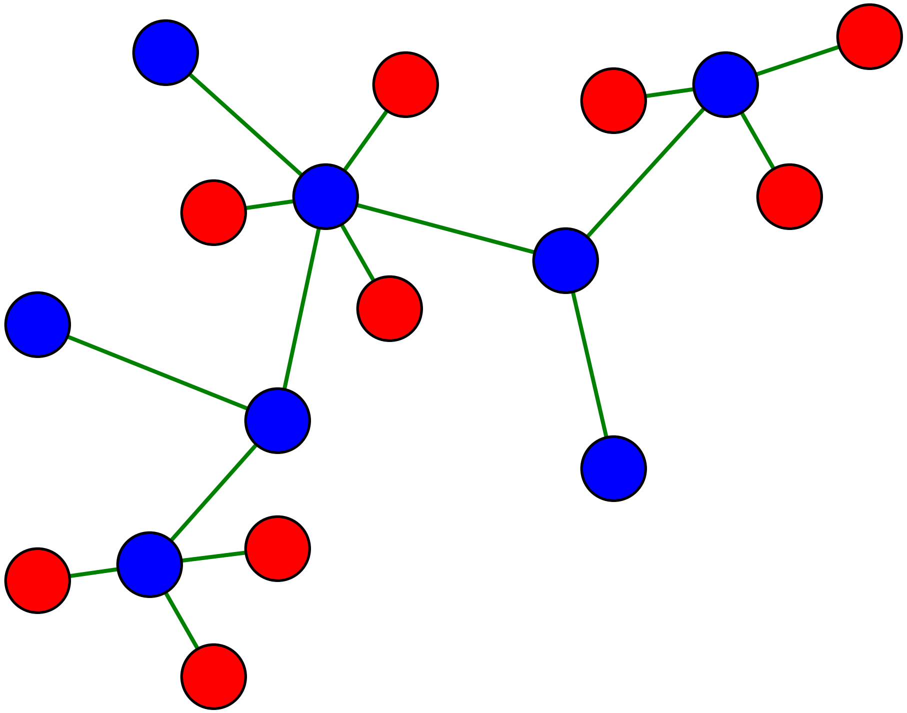
🔵 Full function device

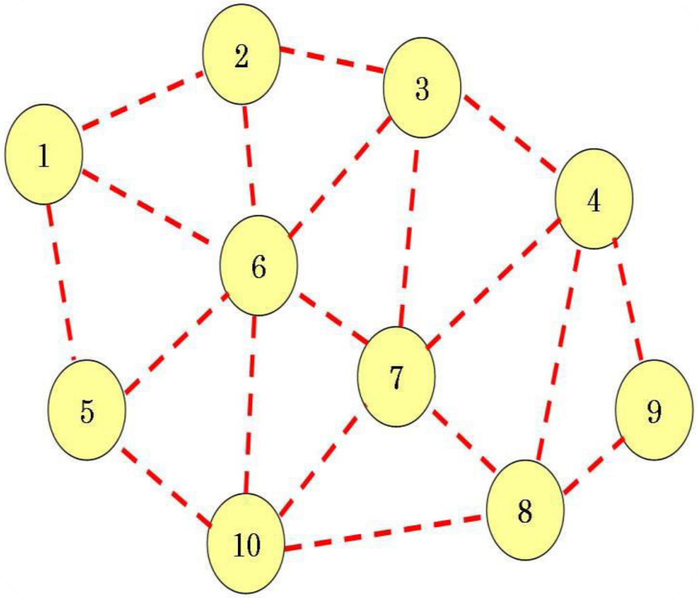
🔴 Reduced function device



Cluster tree

Typical Network Topologies





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

Mesh Networks: Each node must acquire and transmit its own data, as well as act as a relay for other nodes to propagate data. **Examples:** Wireless light switching, Music school practice rooms.

Addressing

- All devices have 64 bit IEEE addresses
- Short addresses can be allocated
- Addressing modes:
  - Network + device identifier (star)
  - Source/destination identifier (peer-peer)
  - 2 Symbols = 1 Byte (8 Bits)
  - Each Symbol = 4 bits.

Radio Specifications

- Clear channel assessment (CCA)
- **CCA mode 1:** energy above threshold (lowest)
- **CCA mode 2:** carrier sense (medium)
- **CCA mode 3:** carrier sense with energy above threshold (strongest)
- The energy detection threshold shall be at most 10 dB above the specified receiver sensitivity.
- The **CCA detection time shall equal to 8 symbol** periods

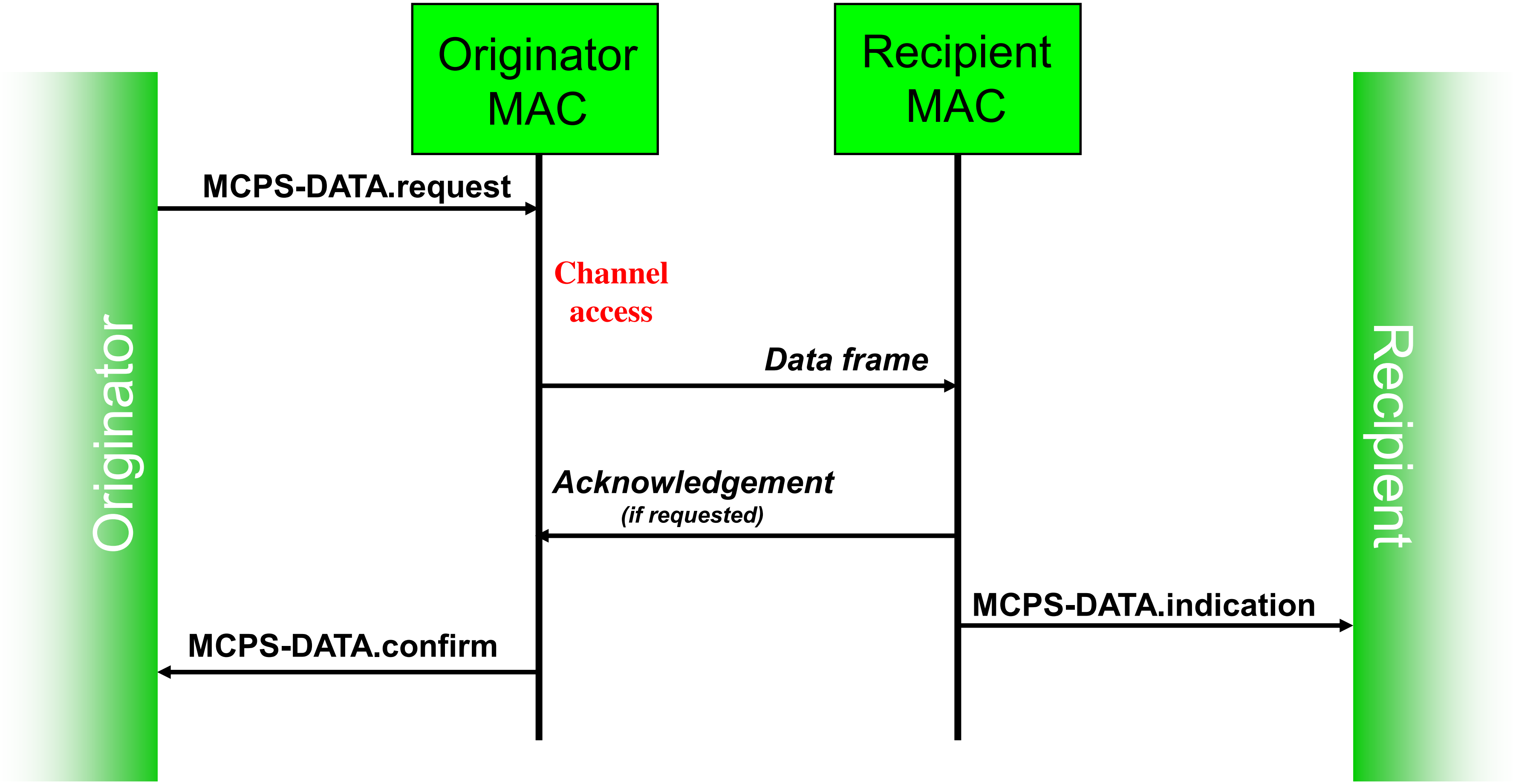
General Frame Structure

- **4 Types of MAC Frames:**
  - **Data Frame**
  - **Beacon Frame**
  - **Acknowledgment Frame**
  - **MAC Command Frame**

Traffic Types:

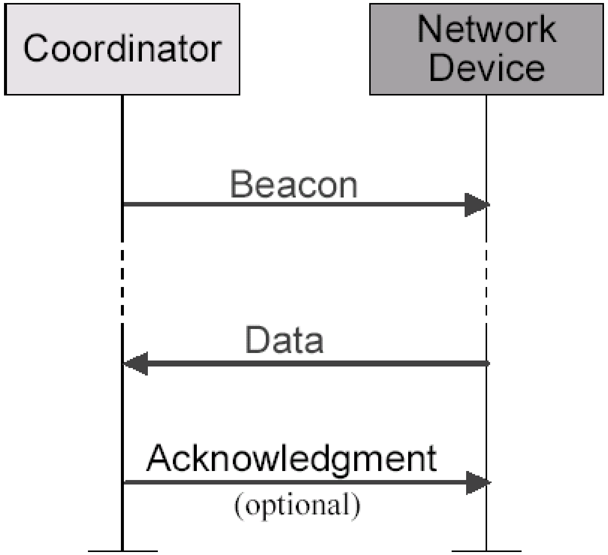
- **Periodic data**
  - Application defined rate (e.g. sensors)
- **Intermittent data**
  - Application/external stimulus defined rate (e.g. light switch)
- **Repetitive low latency data**
  - Allocation of time slots (e.g. mouse)

Data Transfer Model

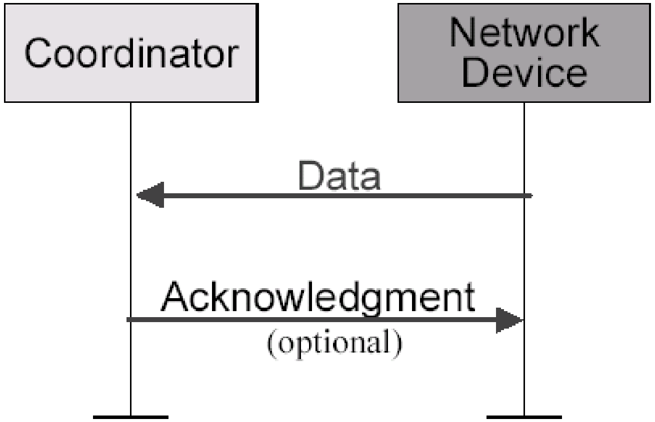


Data Transfer Model

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



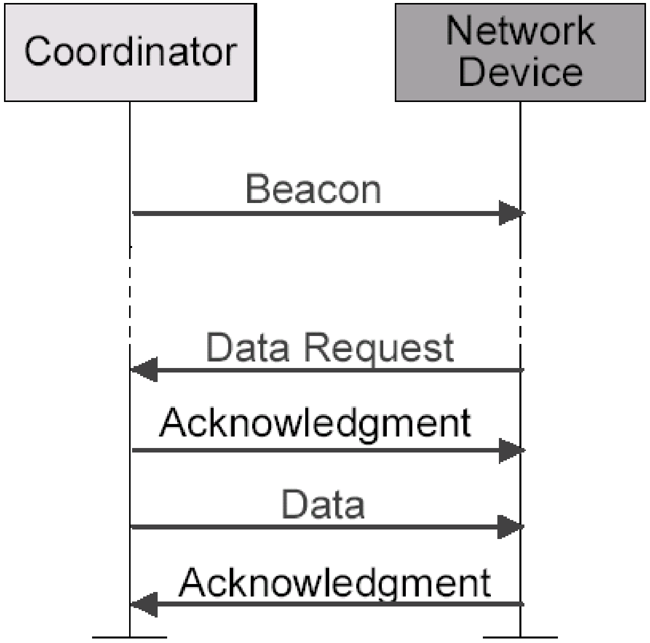
Communication to a coordinator
In a beacon-enabled network



Communication to a coordinator
In a non beacon-enabled network

Data Transfer Model

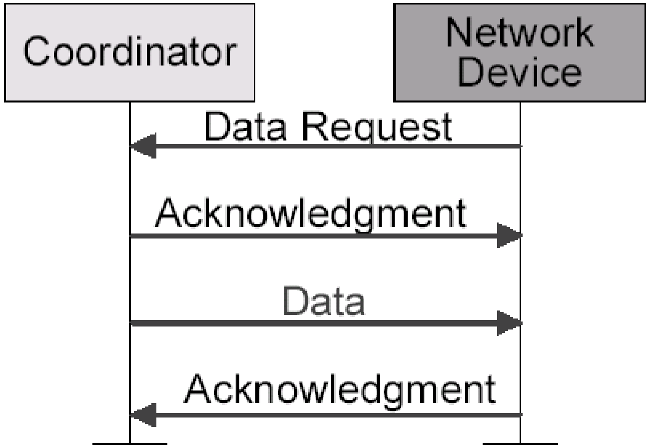
- Data transferred from coordinator to device
  - In a beacon-enable network, the coordinator indicates in the beacon that "data is pending."
  - Device periodically listens to the beacon and transmits a MAC command request using slotted CSMA/CA if necessary.



Communication from a coordinator
In a beacon-enabled network

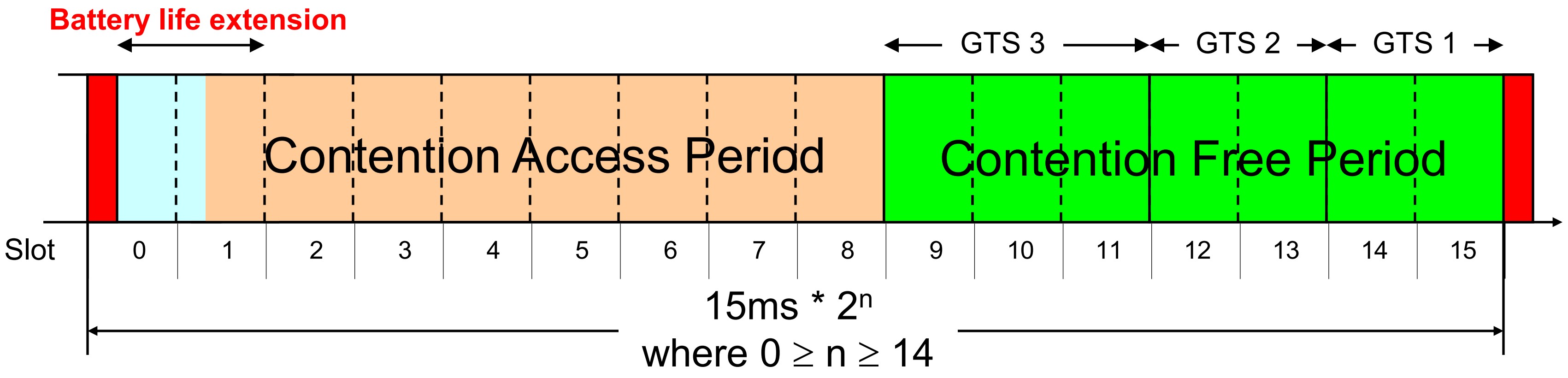
Data Transfer Model

- Data transferred from coordinator to device
  - In a non beacon-enable network, a device transmits a MAC command request using unslotted CSMA/CA.
    - similar to unslotted ALOHA
  - If the coordinator has its pending data, the coordinator transmits data frame using unslotted CSMA/CA.
  - Otherwise, the coordinator transmits a data frame with zero length payload.



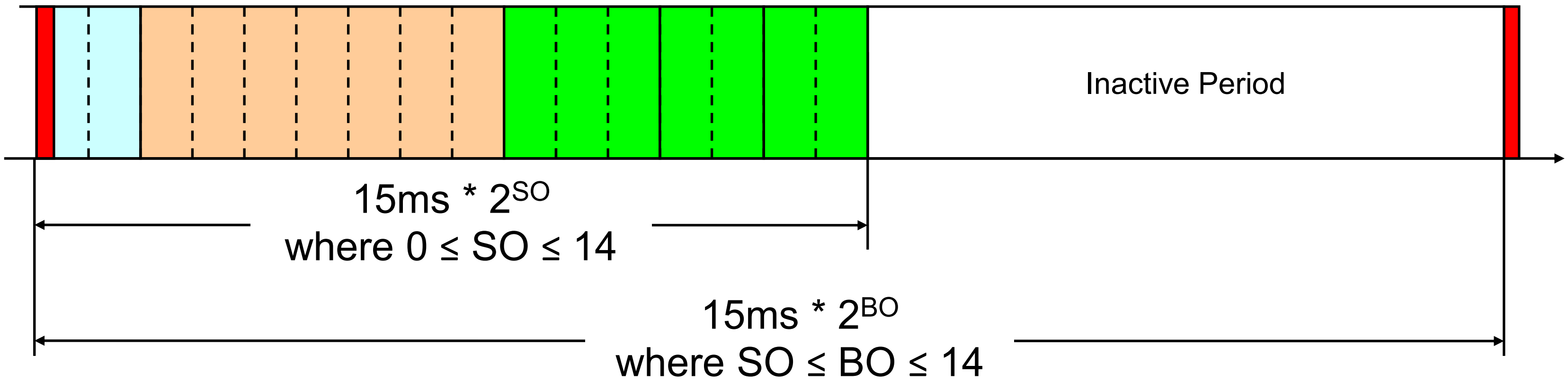
Communication from a coordinator in a non beacon-enabled network

Super Frame Structure



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].

Super Frame Structure



BI = Beacon Interval
SD = Superframe Duration

SO = Superframe order
BO = Beacon order

- BI = aBaseSuperframeDuration $\times 2^{\mathbf{BO}}$
- SD = aBaseSuperframeDuration $\times\ 2^{\mathbf{SO}}$
- A base superframe is the time duration of **smallest** superframe in symbols (**960 symbols**)
- CFP is optional. If the CFP is zero length, the CAP is the total active portion of the superframe.
- The CAP shall be at least **440 symbols**.

All durations

- Each superframe has 16 slots (without inactive period).
- Number of symbols required to form a superframe (aBaseSuperframeDuration) = aBaseSlotDuration*aNumSuperframeSlots
- Number of symbols in each slot (aBaseSlotDuration) = **60 symbols** (When SO=0)
- Number of slots in a superframe (aNumSuperframeSlots) = **16 slots**

All durations

- So, Number of symbols required to form a superframe (aBaseSuperframeDuration) = **60*16=960 symbols (When SO=0)**
- Out of 960 symbols, CAP should be at least 440symbols.
- Duration of each symbol = **16 µsec**
- So, smallest duration of each superframe (CAP+CFP) = 16 µsec * 960 symbols = **15360 µsec**

All durations

- **Each symbol** = **4 bits** (2.4 GHz ISM Band)
- Since each slot has 60 symbols, so each slot = 60 *4 bits = **30 Bytes**
- But, **Each "contention slot" is of 20 symbols long.**
- **CAP can have 440/20=22 contention slots.**
- *aUnitBackoffPeriod:* ***20 symbols***
- *aTurnaroundTime (*RX-to-TX or TX-to-RX maximum turnaround time (in symbol periods)*:* ***12 symbols***
- *aMaxPHYPacketSize:* The maximum PSDU size (in octets) the PHY shall be able to receive: **127 Bytes**

Super Frame Structure

- A superframe is divided into two parts
- **Inactive:** all stations sleep
- **Active:**
- Active period will be divided into **16** slots
- 16 slots can further divided into two parts
- Contention access period (CAP)
- Contention free period (CFP)
- (These slots are “MACRO” slots.)

Super Frame Structure

- There are two parameters:
  - SO: to determine the length of the active period
  - BO: to determine the length of the beacon interval.
- In CFP, a GTS may consist of multiple slots, all of which are assigned to a single device, for either transmission (t-GTS) or reception (r-GTS).
  - GTS = guaranteed time slots
- In CAP, the concept of slots is not used.
  - Instead, the whole CAP is divided into smaller “contention slots”.
  - **Each “contention slot” is of 20 symbols long.**
    - This is used as the smallest unit for contention backoff.
  - Then devices contend in a slotted CSMA/CA manner.

Super Frame Structure

- Two types of channel access mechanism, based on the network configuration:
  - In non-beacon-enabled networks → unslotted CSMA/CA channel access mechanism
  - In beacon-enabled networks → slotted CSMA/CA channel access mechanism
    - The superframe structure will be used.

CSMA/CA Mechanism

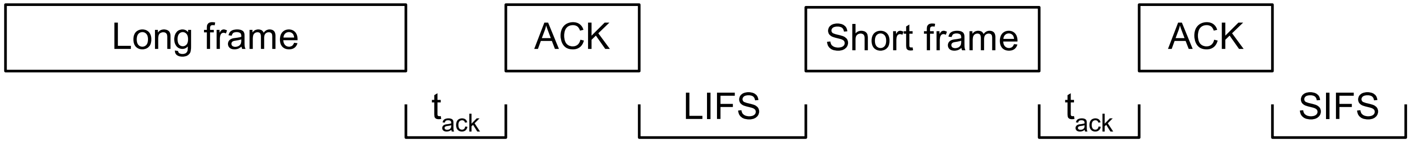
- The **backoff period boundaries** of every device in the PAN shall be **aligned with the superframe slot boundaries of the PAN coordinator**
  - i.e. the **start of first backoff period of each device is aligned with the start of the beacon transmis**sion
- The MAC sublayer shall ensure that the PHY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

CSMA/CA Mechanism

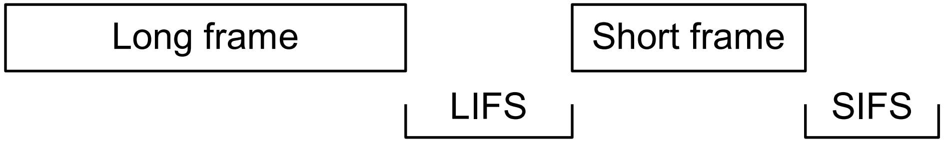
- Each device shall maintain three variables for each transmission attempt
  - **NB:** number of slots the CSMA/CA algorithm is required to backoff while attempting the current transmission.
  - **BE:** the backoff exponent which is related to how many backoff periods a device shall wait before attempting to assess a channel
  - **CW:** **(a special design)**
    - **Contention window length, the number of backoff slots that needs to be clear of channel activity before transmission can commence.**
    - **It is initialized to 2 and reset to 2 if the channel is sensed to be busy.**
      - **So a station has to detect two CCA before contending.**

Inter-frame Spacing

Acknowledged transmission



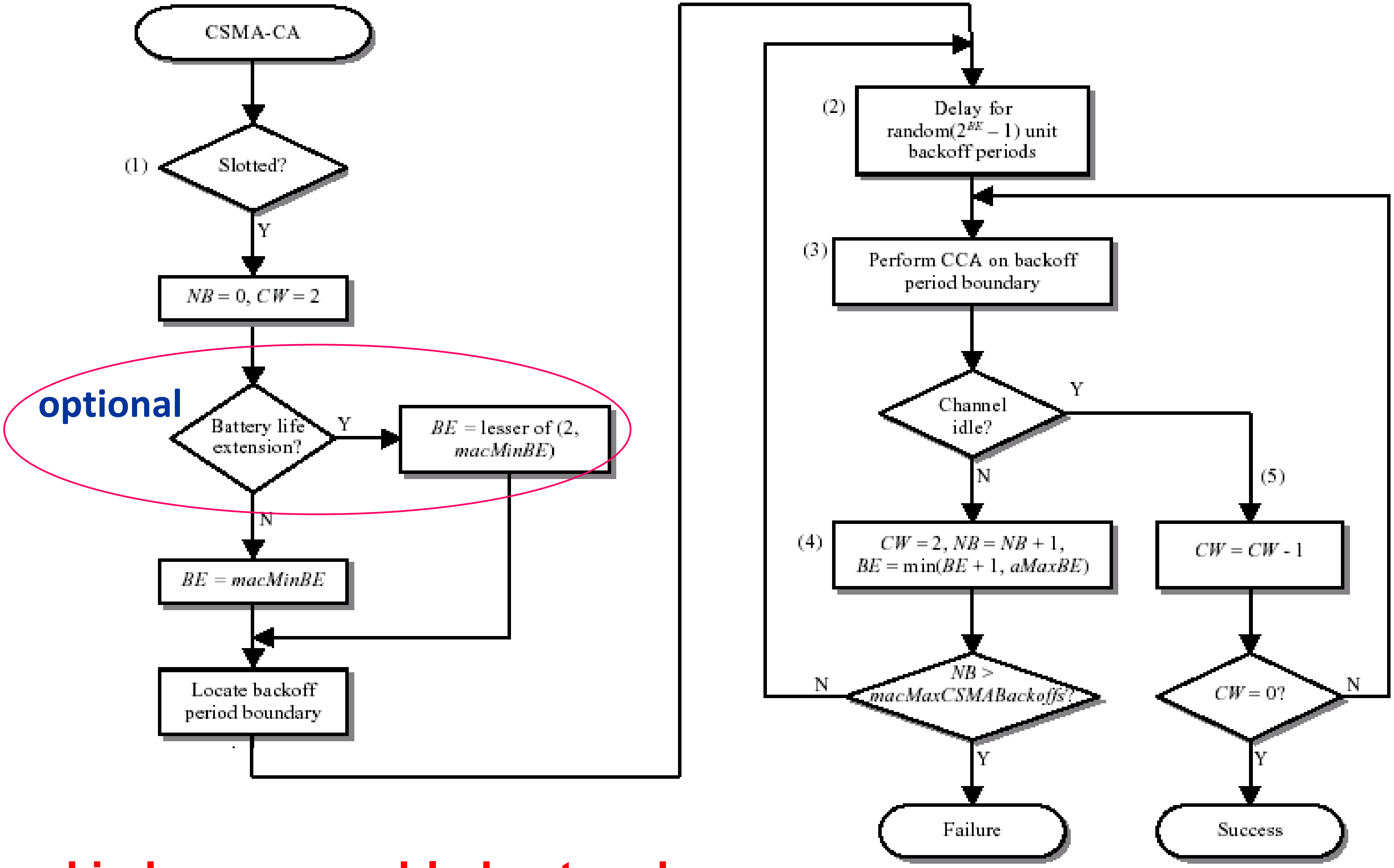
Unacknowledged transmission



aTurnaroundTime $\le t_{ack} \le$ (*aTurnaroundTime* (12 symbols) + *aUnitBackoffPeriod* (20 symbols))
LIFS > *aMaxLIFSPeriod* (40 symbols)
SIFS > *aMacSIFSPeriod* (12 symbols)

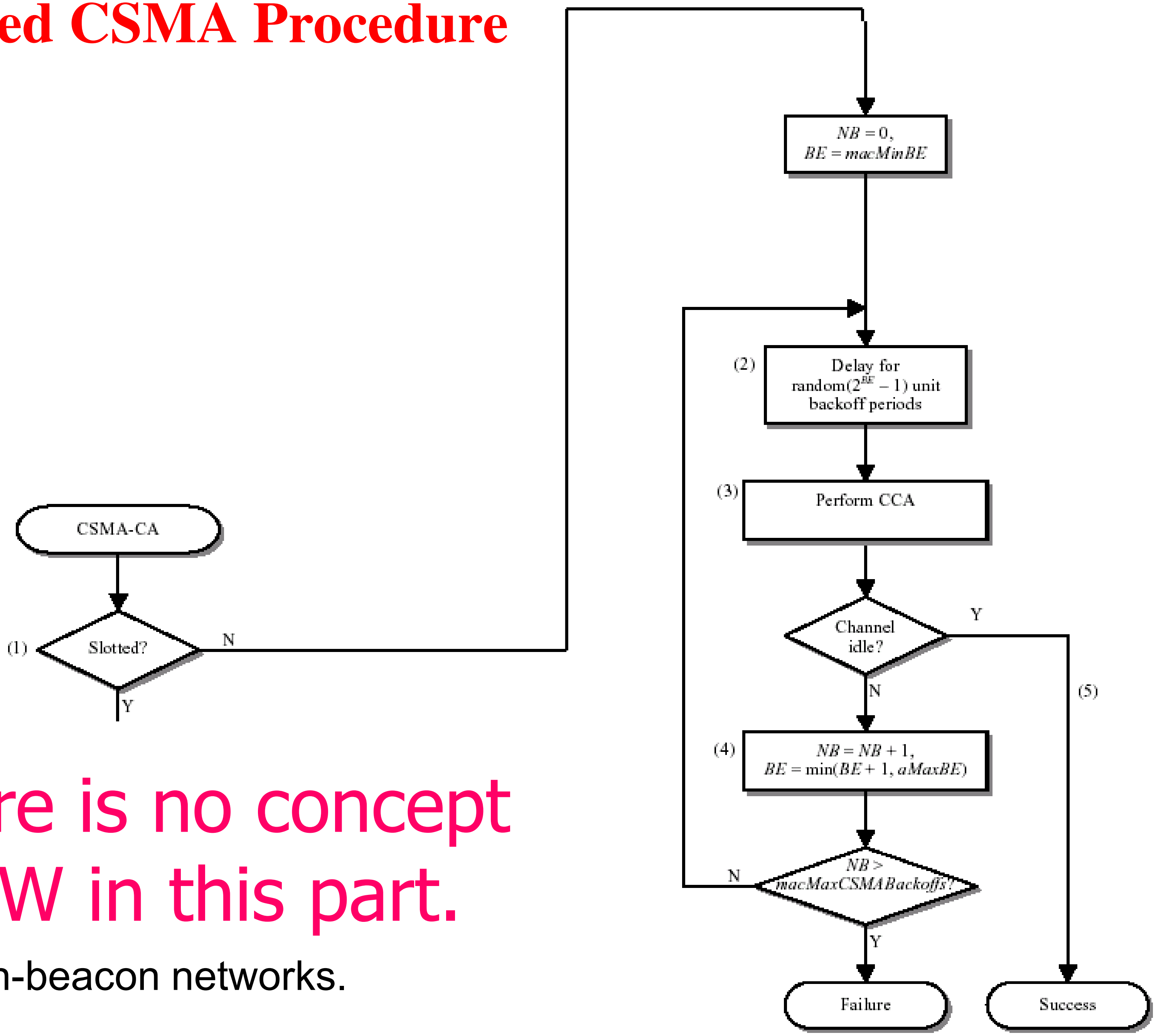
For frames ≤ *aMaxSIFSFrameSize use short inter-frame spacing (SIFS)*
For frames > *aMaxSIFSFrameSize use long inter-frame spacing (LIFS)*

Slotted CSMA Procedure



Used in beacon enabled networks.

Un-slotted CSMA Procedure



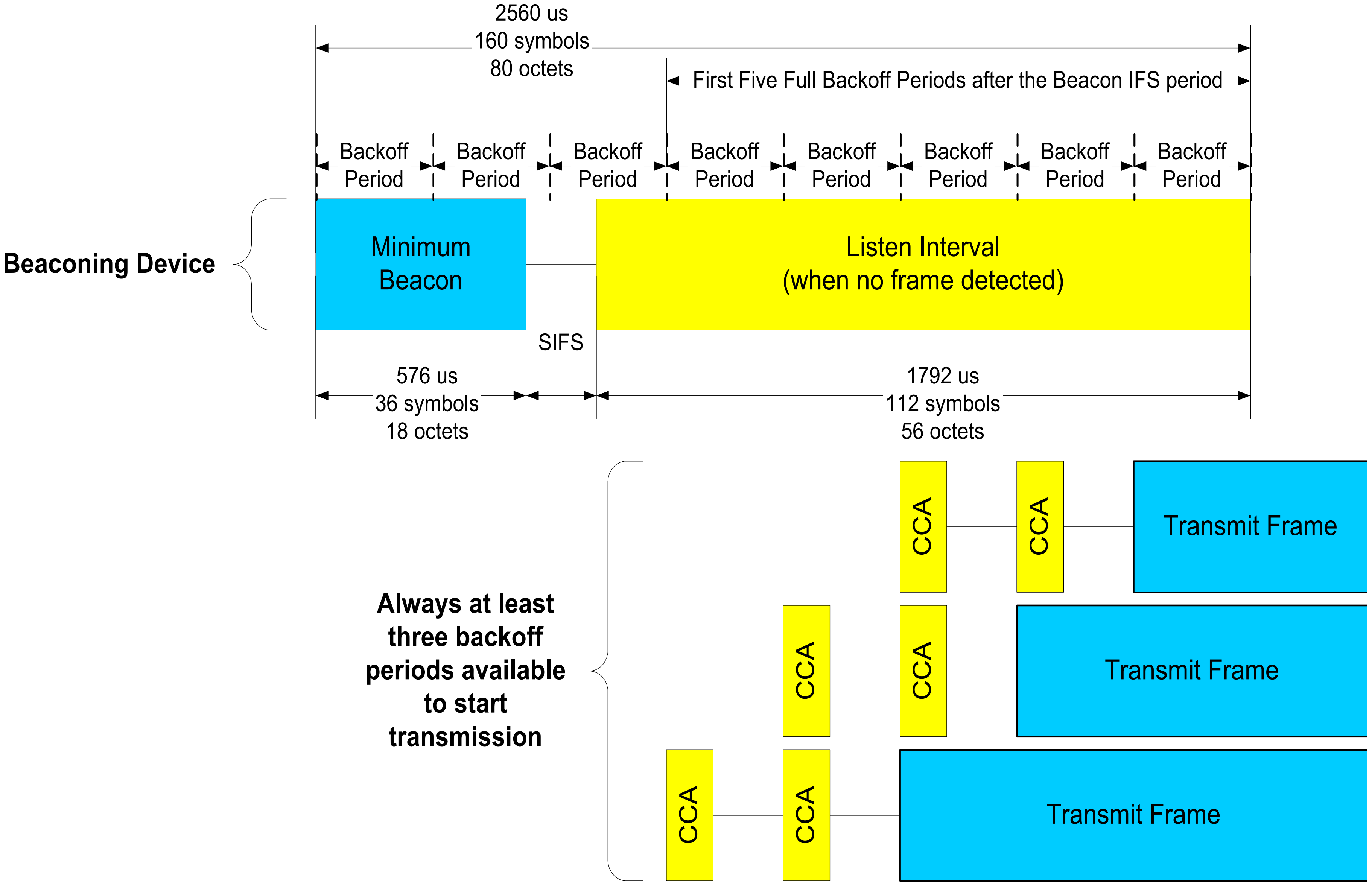
There is no concept of CW in this part.

Used in non-beacon networks.

Battery Life Extension

- Power Consumption Considerations
  - In the applications that use this standard, most of the devices will be battery powered.
  - Battery powered devices will require duty-cycling to reduce power consumption.
  - The application designer should decide on the balance between battery consumption and message latency.
- Battery Life Extension:
  - A station can only send in the first **FIVE slots** after the beacon.
    - Beacons are variable lengths.
    - SIFS has to be taken, after which 2 CCA’s are needed before contending.
    - **If a station does not find a chance to transmit in the first 5 slots, it has to wait until the next beacon.**

Battery Life Extension



GTS Concept

- 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.
  - … and is announced in the beacon.
- The PAN coordinator can allocate up to seven 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 Concept

- A GTS can be de-allocated in two ways:
  - At any time at the discretion of the PAN coordinator.
  - 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
- The PAN coordinator should store the info of devices with GTS:
  - including starting slot, length, direction, and associated device address.

GTS Concept

- 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.
  - Each GTS may consist of multiple “MACRO” slots.
- 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 of an RFD is optional

IEEE 802.15.4e Standard

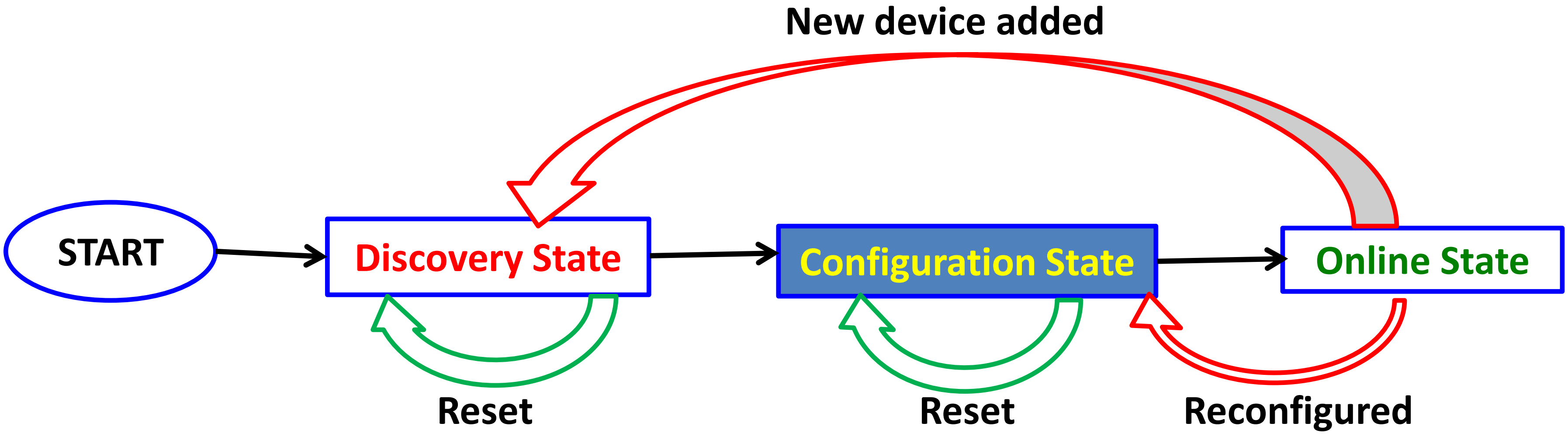
(Amendment to IEEE Std 802.15.4-2011)

Published: 16 April 2012

Network Topology

- Three different types of PANs.
- **Type 1:** A Low Latency Deterministic Network **(LLDN)- operates in a star topology**.
- **Type 2:** Time Slotted Channel Hopping **(TSCH)** PANs- **Topology independent and can be used in star topologies as well as partial or full mesh topologies.**
- **Type 3:** Deterministic and Synchronous Multi-channel Extension **(DSME):** Supports **both star and peer-to-peer network topologies**.

LLDN transmission states



- **Step 1: Discovery state:** New devices are discovered during network setup or for the addition of new devices to an existing network.
- **Step 2: Configuration state:** Devices are configured.
- **Step 3: Online state:** After the successful completion of the configuration state, nodes can go into online state. Data and readings from the devices can only be transmitted during online state.
- In order to reconfigure a network, the configuration state can be started again.

Discovery State (Ref: Page 33)

- In the Discovery state, the superframe contains only the timeslot for the beacon and two management timeslots, one downlink and one uplink.
- A new device scans the different channels until it detects an LLDN PAN coordinator sending beacons that indicates the Discovery state.
- If a new device received a beacon indicating the Discovery state, it attempts to access the medium in the uplink management timeslot in accordance with slotted CSMA-CA mechanism (Ref: 5.1.1.4.4) in order to send a Discover Response frame to the LLDN PAN coordinator.
- The Discover Response frame (Ref: 5.3.10.1) contains the current configuration of the device.
- The new device shall repeat sending the Discover Response frame until it receives an acknowledgment frame (Ref: 5.2.2.5.4) for it or the Discovery state is stopped by the LLDN PAN coordinator.

- Problem: Delay analysis due to collision when more than one node scan the same channel and use CSMA-CA to send Discover Response frame.

Configuration State (Ref: Page 34)

- It is the second step during network setup and is used for network reconfiguration.
- In this state, the superframe contains only the timeslot for the beacon and two management timeslots, one downlink and one uplink **(Same as Discovery state).**
- If a device received a beacon indicating configuration state**, it tries to get access to the transmission medium in the uplink management timeslot (HOW)** in order to send a Configuration Status frame (Ref: 5.3.10.2) to the LLDN PAN coordinator.
- The Configuration Status frame contains the current configuration of the device.
- The new device shall **repeat sending the Configuration Status frame** until it receives a Configuration Request frame (Ref: 5.3.10.3) for it or the Configuration state is stopped by the LLDN PAN coordinator.
- The Configuration Request frame contains the new configuration for the receiving device.
- After successfully receiving the Configuration Request frame, the device sends an acknowledgment frame (Ref: 5.2.2.5.4-same as discovery phase) to the LLDN PAN coordinator.

Online State (Ref: Page 35)

- User data is only sent during Online state.
- The superframe starts with a beacon and is followed by several timeslots.
- The devices can send their data during the timeslots assigned to them during the configuration state and different types of timeslots are considered.
- The existence and length of management timeslots in the Online state are contained in the Configuration Request frame.
- Successful reception of data frames by the LLDN PAN coordinator is acknowledged in the Group Acknowledgment bitmap of the beacon frame of the next superframe.
- Or in a separate Data Group Acknowledgment frame.
- **This case is applicable for both uplink timeslots and bidirectional timeslots, if the transmission direction is uplink.**

Retransmission policy (Ref: Page 34)

- **If retransmission timeslots are configured**, the retransmission slots are assigned to the owners of the first *macLLDNnumRetransmitTS* with the **corresponding bit in the group acknowledgment bitmap set to zero**.
- Each LLDN device shall execute the algorithm (Ref: Figure 34e) in order **to determine its retransmission timeslot.**
- The LLDN PAN coordinator has to execute a similar algorithm in order **to determine the senders of the frames in the retransmission slots.**

Retransmission policy (Ref: Page 34)

- Suppose LLDN device has been assigned to uplink timeslot **“s”.**
- **Ack[s]:** Represents the uplink success of the LLDN device.
- If the data transmission of the device has failed and has not been acknowledged, **ack[s] is assigned to zero.**
- LLDN device determines the **number of failed transmissions (NFT)** in previous timeslots excluding retransmission timeslots.
- This number of failed transmissions (NFT), is the number of **Ack[i]** equal to 0 with (*macLLDNnumRetransmitTS*+1) ≤ i ≤ (s−1).

Retransmission policy (Ref: Page 34)

- A retransmission is possible:
- If number of failed transmissions (NFT) **<** *macLLDNnumRetransmitTS*.
- The device retransmits its data in retransmission timeslot (NFT+1).
- If the number of failed transmissions NFT **≥** *macLLDNnumRetransmitTS*, a retransmission is not possible.

Retransmission policy (Ref: Fig 34e)

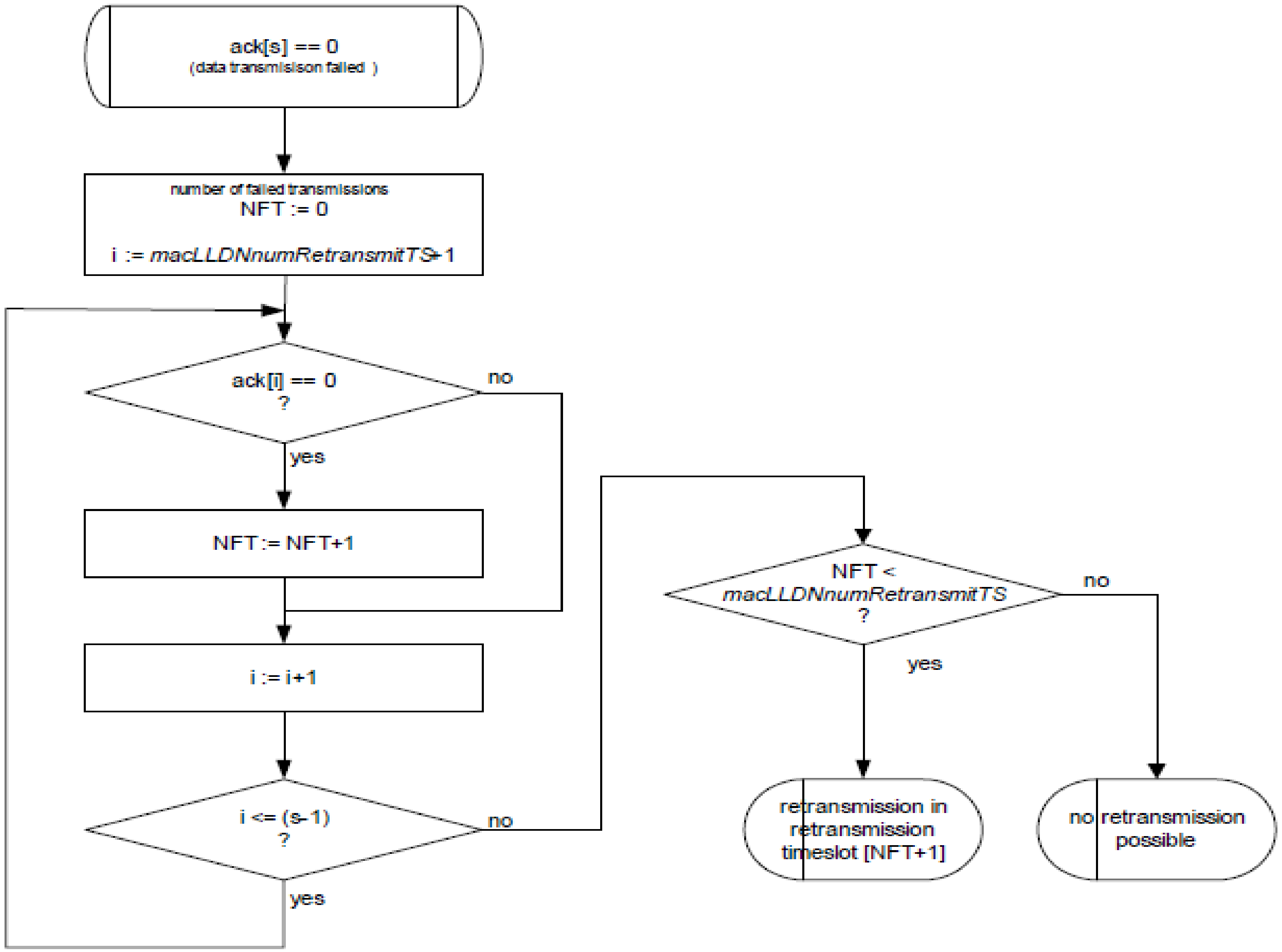


Figure 34e—Retransmission Slot Algorithm

Data Transfer Model

- Proposed data transfer model considers two types of nodes
- **LLDN Node**
- **LLDN PAN Coordinator**
- Data Transfer is made:
- From the LLDN nodes to the LLDN PAN Coordinator.
- From LLDN PAN Coordinator to the LLDN nodes.

Data Transfer Model

- **Data transfer to an LLDN PAN coordinator**
- A node transfers data either:
- **In a dedicated time slot**
- **Or in shared group time slot**
- In the dedicated time slot, a node has exclusive right to transmit data in its assigned time slot.
- In the shared group time slot, a node has exclusive right to transmit data, only if it is the slot owner.
- Else a node has to compete using CSMA-CA to get that slot (in the shared group time slot).

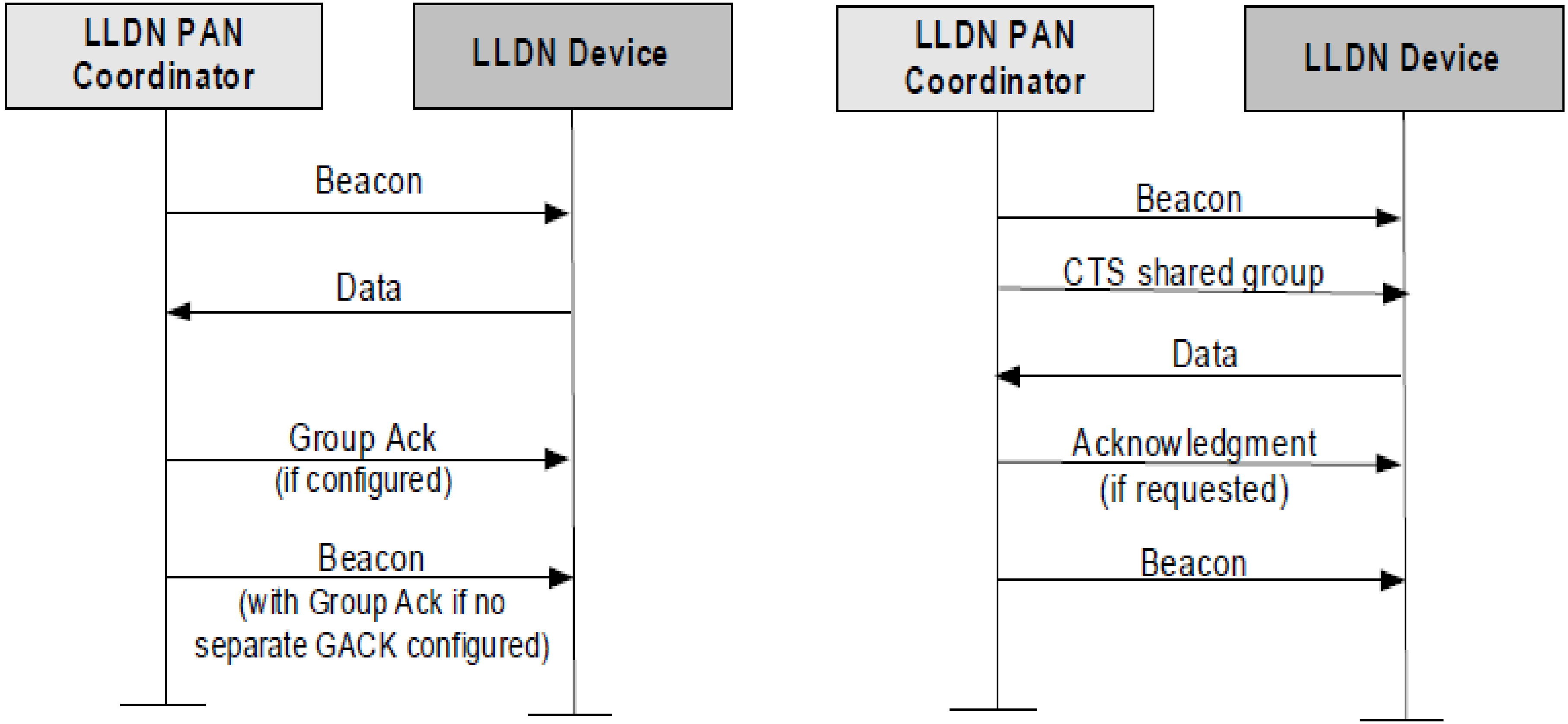
Data transfer to an LLDN PAN coordinator (UPLINK)

- When a node wishes to transfer data to an LLDN PAN coordinator, it first listens for the network beacon.
- When the beacon is found, the device synchronizes to the superframe structure of the PAN Coordinator.
- At its assigned timeslot, the device transmits its data frame to the LLDN PAN coordinator.
- A device transmits its data frame without using CSMA-CA in a dedicated timeslot or as slot owner of a shared group time slot.
- If the device transmits its data frame in a shared group timeslot and is not the slot owner, the data frame is transmitted using slotted CSMA-CA

Data transfer to an LLDN PAN coordinator (UPLINK)

- The LLDN PAN coordinator may acknowledge the successful reception of the data by transmitting an optional acknowledgment frame.
- Successful data transmissions in dedicated timeslots or by the slot owner are acknowledged by the LLDN PAN coordinator with a Group Acknowledgment
- Either in the **next beacon** or as a **separate group acknowledgment (GACK)** frame.

Data transfer to an LLDN PAN coordinator (UPLINK)



Dedicated time slot

Shared group time slot

Figure 4c—Communication to a PAN coordinator in an LLDN

Data transfer from an LLDN PAN coordinator (DOWNLINK)

- **Data transfer from an LLDN PAN coordinator.**
- A data transfer from an LLDN PAN coordinator is only possible if the Transmission Direction field in the Flags field of the beacon indicates downlink direction.
- When the LLDN PAN coordinator wishes to transfer data to an LLDN device assigned to a bidirectional timeslot, it indicates in the network beacon that the transmission direction is downlink.
- At the appropriate time, the LLDN PAN coordinator transmits its data frame to the device without using CSMACA.

Data transfer from an LLDN PAN coordinator (DOWNLINK)

- The device may acknowledge the successful reception of the data by transmitting an acknowledgment frame to the LLDN PAN coordinator in the same timeslot of the next superframe.
- In order to do so, the transmission direction has to be uplink in that superframe.

Data transfer from an LLDN PAN coordinator (DOWNLINK)

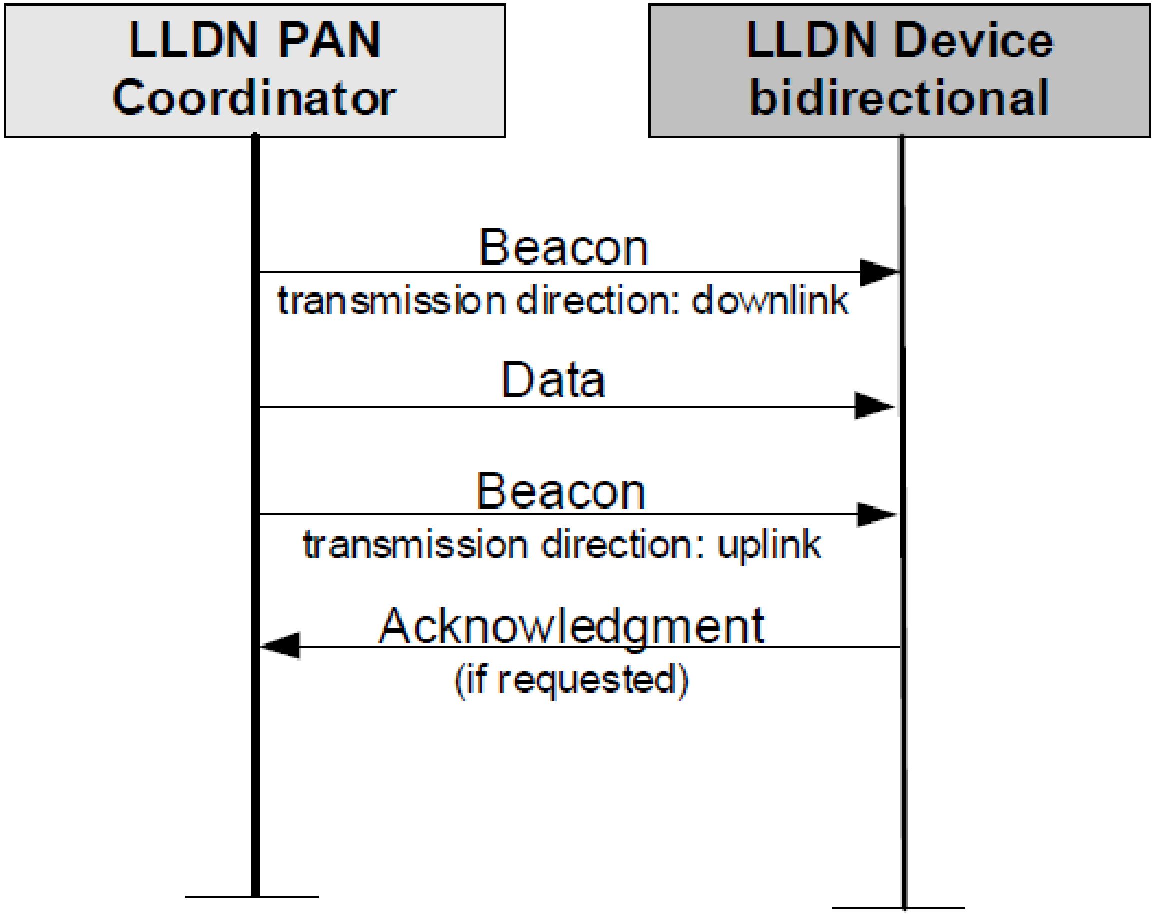


Figure 4d—Communication from a PAN coordinator to a device in an LLDN

LLDN CSMA-CA mechanism

- LLDNs use a slotted CSMA-CA channel access mechanism
- **For management timeslots**
- **For shared group timeslots**
- Each time a device wishes to transmit data frames with CSMA-CA at the appropriate places, it locates the boundary of the next backoff slot and then waits for a random number of backoff slots.

LLDN CSMA-CA mechanism

- **After the random backoff :**
- If the channel is busy, the device waits for another random number of backoff slots before trying to access the channel again.
- If the channel is idle, the device begins transmitting on the next available backoff slot boundary.
- Acknowledgment and beacon frames are sent without using a CSMA-CA mechanism.

LLDN CSMA-CA mechanism

- The backoff slots of *aUnitBackoffPeriod* symbols are:
- Aligned with the start of the beacon transmission→ in management timeslots
- Aligned with tSlotTxOwner → in shared group timeslots.
- **The CSMA-CA mechanism is SAME as the IEEE 802.15.4-2011 standard.**

LLDN Superframe structure

- LLDN superframe is divided into:
- A beacon slot,
- Management timeslots (0 slot/2 slots)
- *Data slots (macLLDNnumTimeSlots)* → base timeslots of equal length.

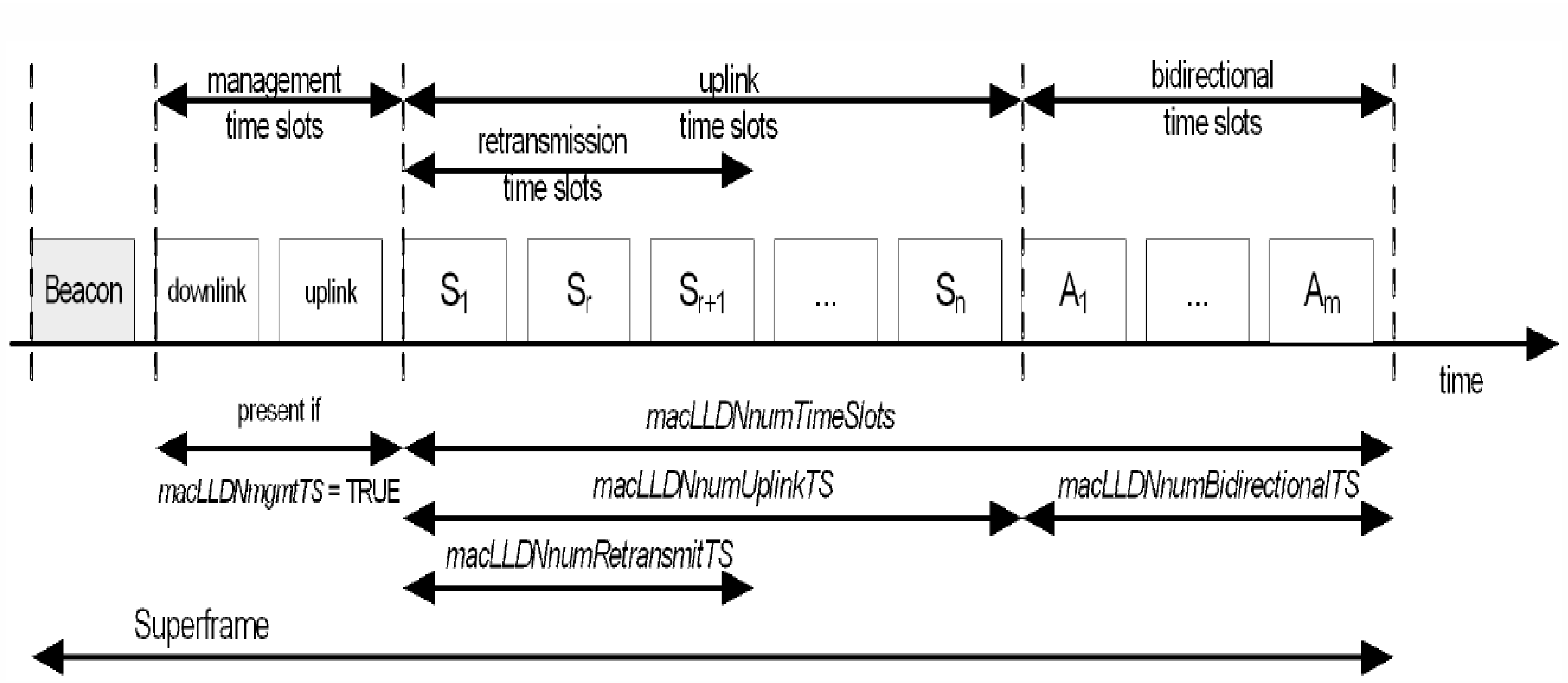
Superframe structure for LLDN PAN

- First timeslot of each superframe contains an LL-Beacon frame.
- LL-Beacon frame is used for synchronization with the superframe structure.
- It is also used for re-synchronization of devices that, for instance, went into power save or sleep mode.
- The beacon timeslot **may** be followed by two management timeslots, one for downlink and one for uplink.
- The remaining timeslots are assigned to the LLDN devices in the network.

Superframe structure for LLDN PAN

- Allocation of time slots could be:
- **Dedicated time slots:**
- The slot owner has access privileges in the timeslot.
- Determination of the sender is achieved through the number of the timeslot.
- **Shared group time slots:**
- More than one device can be assigned to a timeslot.
- The devices use a contention-based access method (CSMA-CA) and a simple addressing scheme with 8-bit addresses in shared group timeslots.

Beacon Timeslot: Always present.
Management Timeslots (optional): One timeslot downlink, one timeslot uplink, presence is configurable during the Configuration state.



Superframe structure for LLDN PAN

- There is **no explicit addressing necessary** inside the frames provided that there is exactly one device assigned to a timeslot.
- Determination of the sender is achieved through the indexing of timeslots.
- If there is more than one device assigned to a timeslot, the timeslot is referred to as shared group timeslot.
- and a simple addressing scheme with 8-bit addresses (*macSimpleAddress)* is used.

Superframe structure for LLDN PAN

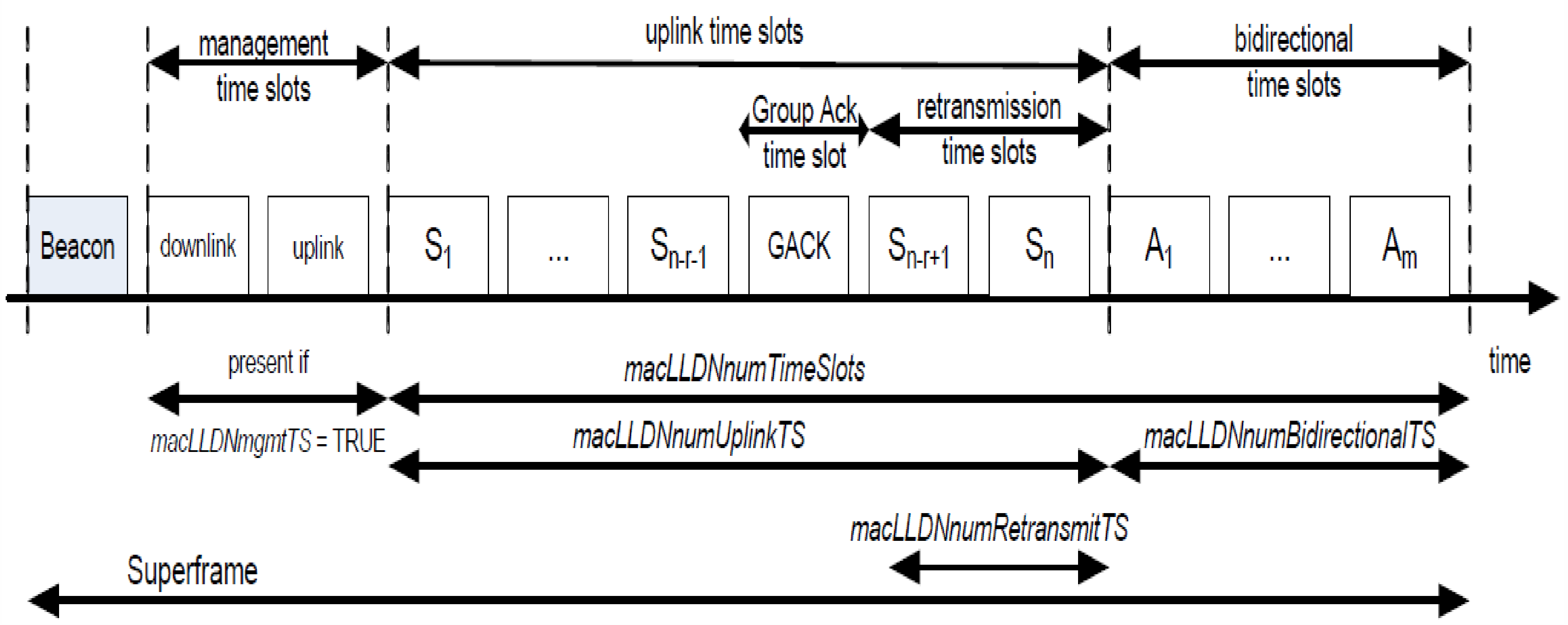
- **Uplink timeslots for LLDN devices:**
- *macLLDNnumUplinkTS* timeslots uplink (unidirectional communication),
- *macLLDNnumRetransmitTS* timeslots **at the beginning can be reserved for retransmissions** according to the Group Acknowledgement field contained in the LL-beacon.
- **Bidirectional timeslots for LLDN devices:** *macLLDNnumBidirectionalTS* timeslots are allocated for uplink/downlink communication.
- (bidirectional communication).

Superframe structure for LLDN PAN

- It is also possible to use a separate Group Acknowledgement (GACK) frame.
- In order to facilitate retransmissions of failed transmissions in the uplink timeslots within the same superframe.
- The use of a separate GACK is configurable during configuration mode.

Superframe structure for LLDN PAN

- This Superframe structure is based on LL Beacons.
- The superframe is divided into a beacon slot, 0 or 2 management timeslots



Superframe Structure

- IEEE 802.15.4e standard allows optional use of different superframe structure.
- **Type 1: Superframe structure as defined in IEEE 802.15.4-2011**
- **Type 2: Superframe structure for LLDN PAN.**
- **Type 3: Superframe structure for TSCH PAN**
- **Type 4: Sperframe structure for DSME PAN**

End