Protocolo IEEE 802.15.4

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IEEE 802.15.4 standard

Agenda

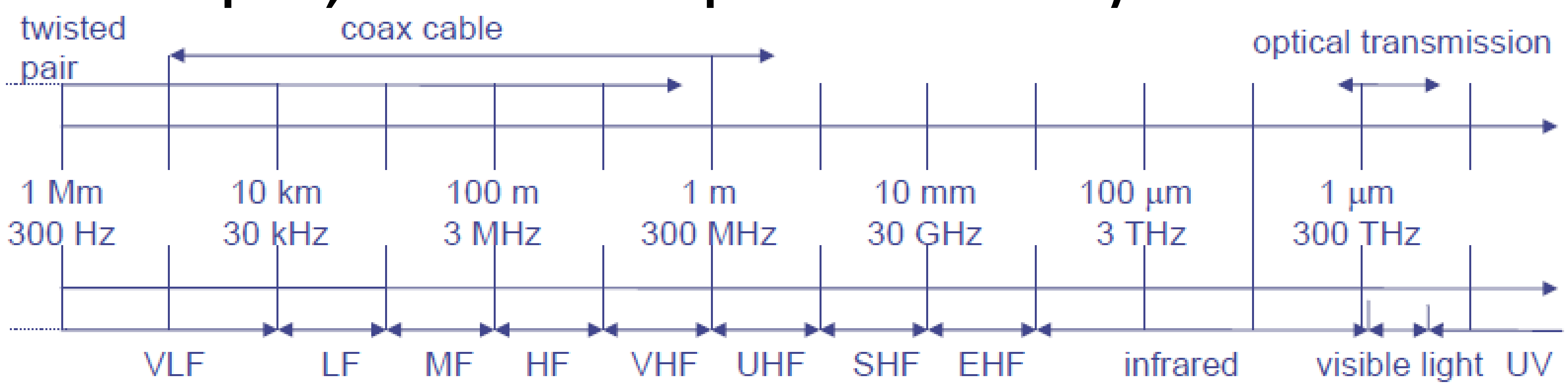
- **Physical Layer for Wireless – Overview**
- MAC Layer for Wireless - Overview
- IEEE 802.15.4 Protocol Overview
- Hardware implementation specs

- Electromagnetic waves propagate in free space between a transmitter and a receiver (transceivers).

- Wireless channels are an unguided medium (in contrast with wired channels, where signals are propagated through the wire).

Frequency Allocation

- In RF-based systems, the carrier frequency determines the propagation characteristics (for example, obstacles penetration).



- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency

UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

Frequency Band

- Since a single frequency (carrier) does not provide communication capacity, a Frequency Band is assigned.
  - When the carrier is modulated, multiple frequencies around the carrier conform a band.
- The range of radio frequencies is subject to Regulation, to avoid unwanted interference between different users and systems.

Physical Layer
Communication Fundamentals over Wireless Channels
ISM license-free band

- ISM (Industrial, Scientific and Medical) band is unlicensed (although some restrictions apply).

The ISM bands defined by the ITU-R are:

Frequency range		Bandwidth	Center frequency	Availability
6.765 MHz	6.795 MHz	30 KHz	6.780 MHz	Subject to local acceptance
13.553 MHz	13.567 MHz	14 KHz	13.560 MHz	
26.957 MHz	27.283 MHz	326 KHz	27.120 MHz	
40.660 MHz	40.700 MHz	40 KHz	40.680 MHz	
433.050 MHz	434.790 MHz	1.84 MHz	433.920 MHz	Region 1 only and subject to local acceptance
902.000 MHz	928.000 MHz	26 MHz	915.000 MHz	Region 2 only
2.400 GHz	2.500 GHz	100 MHz	2.450 GHz	
5.725 GHz	5.875 GHz	150 MHz	5.800 GHz	
24.000 GHz	24.250 GHz	250 MHz	24.125 GHz	
61.000 GHz	61.500 GHz	500 MHz	61.250 GHz	Subject to local acceptance
122.000 GHz	123.000 GHz	1 GHz	122.500 GHz	Subject to local acceptance
244.000 GHz	246.000 GHz	2 GHz	245.000 GHz	Subject to local acceptance

Regulatory authorities may allocate other parts of the radio spectrum for unlicensed communication systems, but these are not ISM bands.

Physical Layer

Communication Fundamentals over Wireless Channels

ISM license-free band - Considerations

- Interference:
  - Since many systems share same bands, robustness is needed to avoid interference (more complicated modulation schemes need to be used).

- Antenna Efficiency:
  - Defined as the ratio of Radiated Power to the Total Input Power. Antennas efficiency decreases as the ratio of antenna dimension to wavelength decreases. Thus, more energy must be spent.

Physical Layer
Communication Fundamentals over Wireless Channels
Modulation - Demodulation

- In order to transmit information, the carrier is modulated (data is encoded).
- The receiver demodulates the carrier, obtaining the transmitted information.
- This process will generate a band of frequencies centered in the carrier frequency.
- Since the carrier is a sinusoidal, different parameters can be used to encode data;
  - Amplitude
  - Frequency
  - Phase

Physical Layer
Communication Fundamentals over Wireless Channels
Speed of Data Transmission

- Digital Communications → Digital Data exchange → sequence of symbols
- Symbols come from a finite alphabet (channel alphabet).
- Modulation process → symbols from channel alphabet are mapped to one of a finite number of waveforms of the same finite length (symbol duration).
- Examples:
  - Binary modulation → two different waveforms → 2 symbols → 1 bit (0 – 1).
  - 8-ary modulation → 8 different waveforms → 8 symbols → 1 group of 3 bits.

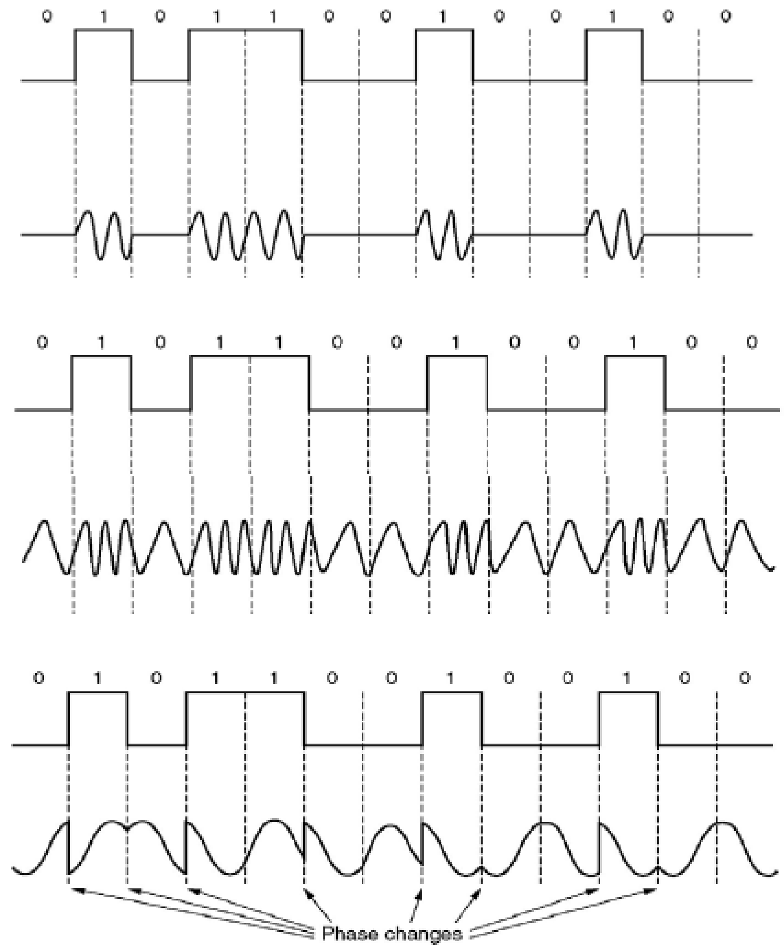
- Speed of Data Transmission/Modulation:
  - Symbol rate: inverse of the symbol duration (also called bit rate for binary modulation).
  - Data rate: bit per seconds the modulator can accepts for transmission (for binary modulation → symbol rate = data rate).
    - For m-ary modulation; Data rate = Symbol rate x Nb of bits encoded in a single waveform.

Physical Layer

Communication Fundamentals over Wireless Channels

Modulation schemes (Keying)

- Carrier representation: $s(t) = A(t)\sin(2\pi f(t)t + \phi(t))$
  - Use data to modify the amplitude of a carrier frequency → ***Amplitude Shift Keying***
  - Use data to modify the ***frequency*** of a carrier frequency → ***Frequency Shift Keying***
  - Use data to modify the ***phase*** of a carrier frequency → ***Phase Shift Keying***



- ASK, FSK and PSK can be used as they are or in combination.
- Common schemes:
  - OOK (On-Off-Keying); special ASK where zeros are mapped to no signal at all (switching off the transmitter).
  - BPSK (2 phases) and QPSK (4 phases)
  - DPSK (difference between successive phases)
  - QAM: ASK + PSK

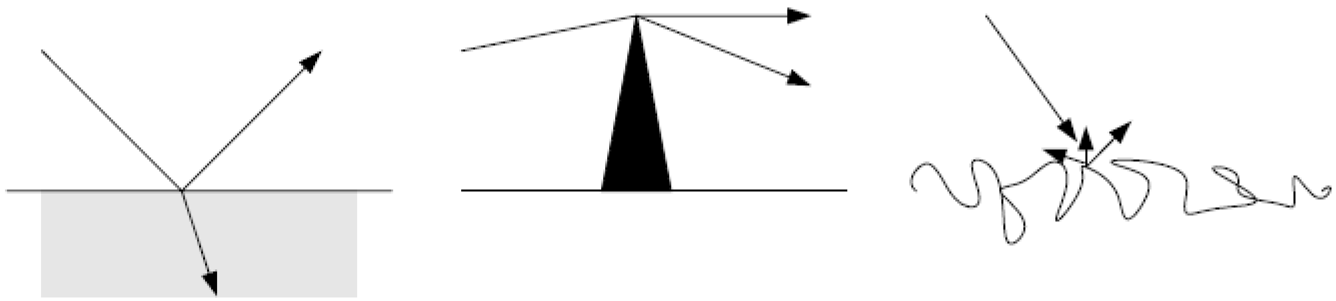
Physical Layer

Communication Fundamentals over Wireless Channels

Wave Propagation effects and noise

- Physical phenomena distort the original transmitted waveform at the receiver → Bit errors.

- Sources of distortion
  - Attenuation – energy is distributed to larger areas with increasing distance
  - Reflection/refraction – bounce of a surface; enter material
  - Diffraction – start "new wave" from a sharp edge
  - Scattering – multiple reflections at rough surfaces
  - Doppler fading – shift in frequencies (loss of center)



Physical Layer

Communication Fundamentals over Wireless Channels

Attenuation results in Path Loss

- Effect of attenuation: received signal strength is a function of the distance *d* between sender and transmitter
- Captured by ***Friis free-space equation***
  - Describes signal strength at distance d relative to some reference distance d_0 < d for which strength is known
  - d_0 is ***far-field distance,*** depends on antenna technology

$$P_{\text{recv}}(d) = \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L}$$

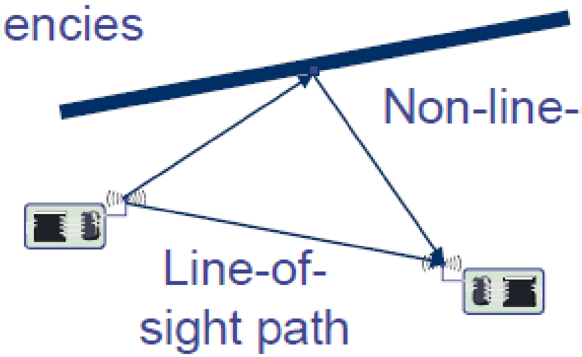
$$= \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d_0^2 \cdot L} \cdot \left(\frac{d_0}{d}\right)^2 = P_{\text{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^2$$

Physical Layer

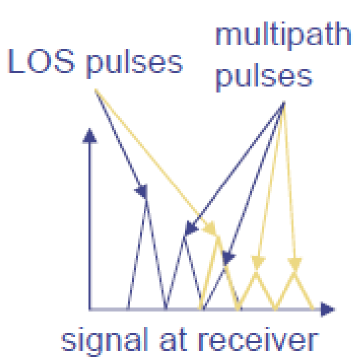
Communication Fundamentals over Wireless Channels

Distortion effects: Non Line-Of-Sight paths

- Because of reflection, scattering, …, radio communication is not limited to direct line of sight communication
  - Effects depend strongly on frequency, thus different behavior at higher frequencies



- Different paths have different lengths = propagation time
  - Results in ***delay spread*** of the wireless channel
  - Closely related to frequency-selective fading properties of the channel
  - With movement: ***fast fading***



Physical Layer
Communication Fundamentals over Wireless Channels
Noise and Interference

- So far: only a single transmitter assumed
  - Only disturbance: self-interference of a signal with multi-path “copies” of itself
- In reality, two further disturbances
  - ***Noise*** – due to effects in receiver electronics, depends on temperature
    - Typical model: an additive Gaussian variable, mean 0, no correlation in time

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2 \right)$$

  - ***Interference*** from third parties
    - Co-channel interference: another sender uses the same spectrum
    - Adjacent-channel interference: another sender uses some other part of the radio spectrum, but receiver filters are not good enough to fully suppress it
- Effect: Received signal is distorted by channel, corrupted by noise and interference
  - What is the result on the received bits?

Physical Layer

Communication Fundamentals over Wireless Channels

Symbols and bit errors

- Extracting symbols out of a distorted/corrupted wave form is fraught with errors
  - Depends essentially on strength of the received signal compared to the corruption
  - Captured by ***signal to noise and interference ratio (SINR)***

$$\mathrm{SINR} = 10 \log_{10} \left(\frac{P_{\mathrm{recv}}}{N_0 + \sum_{i=1}^{k} I_i} \right)$$

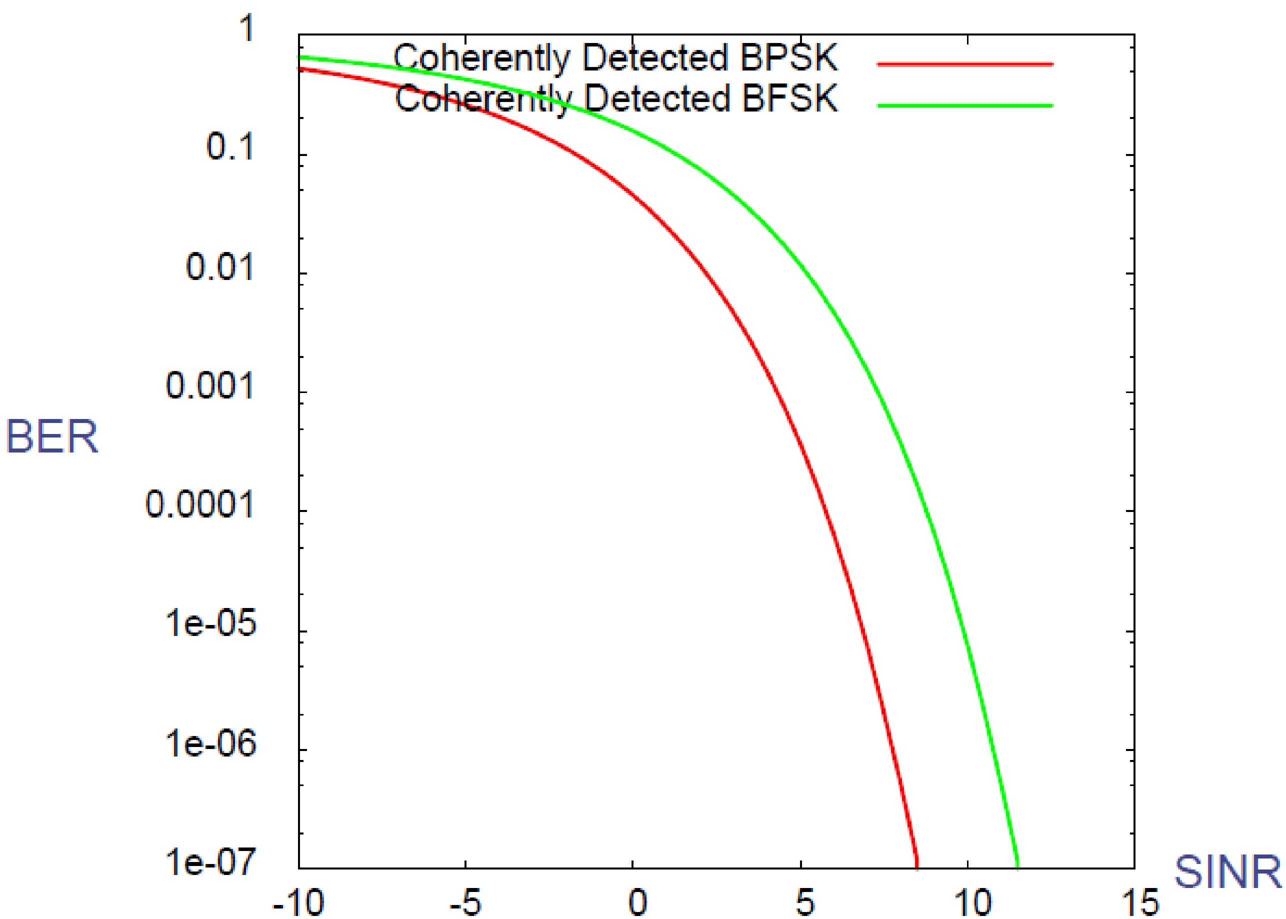
- SINR allows to compute ***bit error rate*** (***BER***) for a given modulation
  - Also depends on data rate (# bits/symbol) of modulation
  - E.g., for simple DPSK, data rate corresponding to bandwidth:

$$\mathrm{BER}(\mathrm{SINR}) = 0.5 e^{-\frac{E_b}{N_0}}$$
$$E_b/N_0 = \mathrm{SINR} \cdot \frac{1}{R}$$

Physical Layer

Communication Fundamentals over Wireless Channels

Examples for SINR → BEP mappings



- Spread-spectrum systems reduce the effects of narrowband noise/interference providing and increased robustness against multipath effects.
- Bandwidth occupied is much larger than that would be really needed to transmit the given user data.
- More complex receiver operation compared to conventional modulation schemes.

Physical Layer
Communication Fundamentals over Wireless Channels
DSSS (Direct Sequence Spread Spectrum)

- Used in IEEE 802.11 and IEEE 802.15.4
- Transmission of data bit of duration tb is replaced by transmission of a finite chip sequence;
  - $c = c1\ c2 \ldots cn$ with $ci \in \{0, 1\}$ if Logical 1
  - $\overline{c1}\ \overline{c2} \ldots \overline{cn}$ (where $\overline{ci}$ is the logical inverse of ci) if Logical 0
- Each chip *ci* has duration ti = tb / n, where n is the spreading factor or gain.
- Proper design of the chip sequences (pseudo-random sequences) cancels delayed version of the chip sequence, reducing multipath fading effects.
- Each chip is modulated with BPSK or QPSK.

Physical Layer

Communication Fundamentals over Wireless Channels

FHSS (Frequency Hopping Spread Spectrum)

- Used in Bluetooth
- Available spectrum is subdivided into a number of equal-sized sub-bands or channels.
- Bluetooth divides their spectrum in the 2.4GHz range into 78 sub-bands 1-MHz wide.
- User data is always transmitted within one channel at a time; it’s bandwidth is thus limited.
- All nodes in the network hop synchronously through the channels according to a prespecified schedule.
- Different networks can share the same geographic area by using nonoverlapping hopping schedules.

Physical Layer

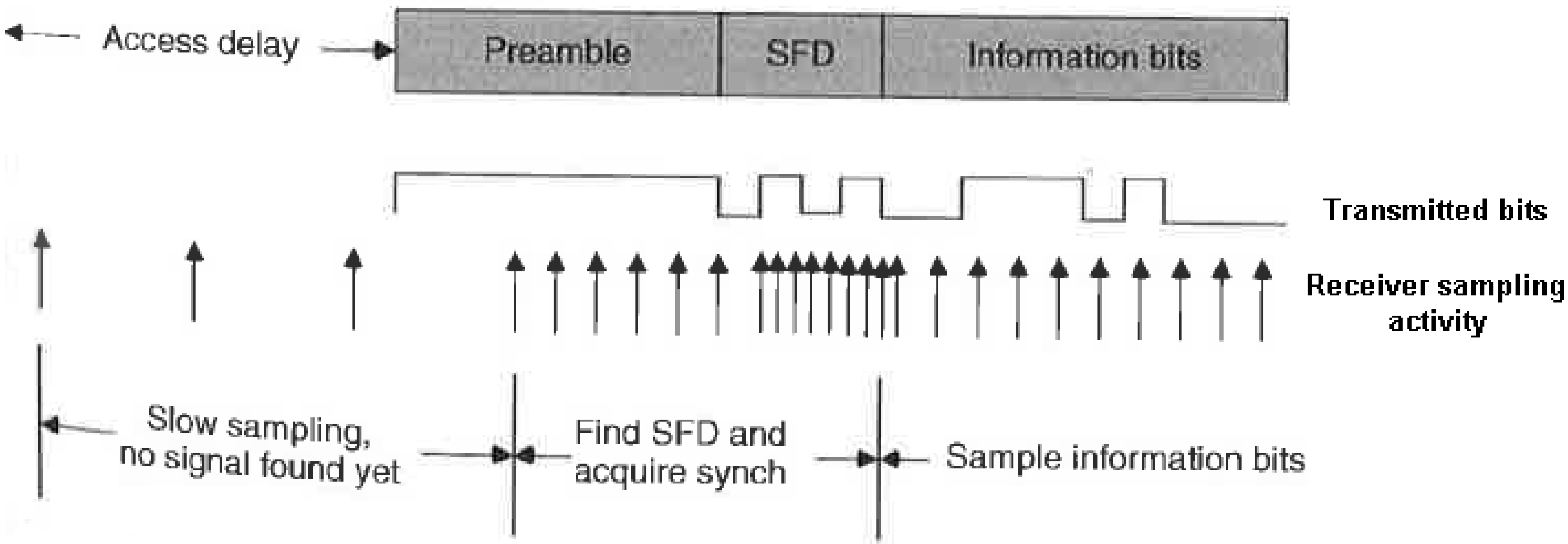
Communication Fundamentals over Wireless Channels

Packet transmission and synchronization

- The PHY layer provides services to the MAC layer.
- MAC layer uses packets or frames as the basic unit of transmission. A frame has a structure.
- From the PHY layer perspective, a frame is just a block of bits. It's function is to modulate and demodulate the carrier with the provided block of bits (frame).
- The receiver, at the PHY layer, must know certain properties of an incoming waveform to make sense of it and detect a frame (frequency, phase, start and end of bits/symbols, and start and end of frames). In other words; it need to be in sync with the transmitter!
- Carrier processing involves use of oscillators and local clocks. Several factors (fabrication process, temperature differences, aging effects, etc) deviate oscillators frequencies from their nominal values. This drift is expressed in ppm (parts per millions).

- To compensate the drift, the receiver has to extract synchronization information from incoming waveform.
- Synchronization levels:
  - – Carrier synchronization
  - – Bit/symbol synchronization
  - – Frame synchronization

Physical Layer
Communication Fundamentals over Wireless Channels
Synchronization example



IEEE 802.15.4 standard

Agenda

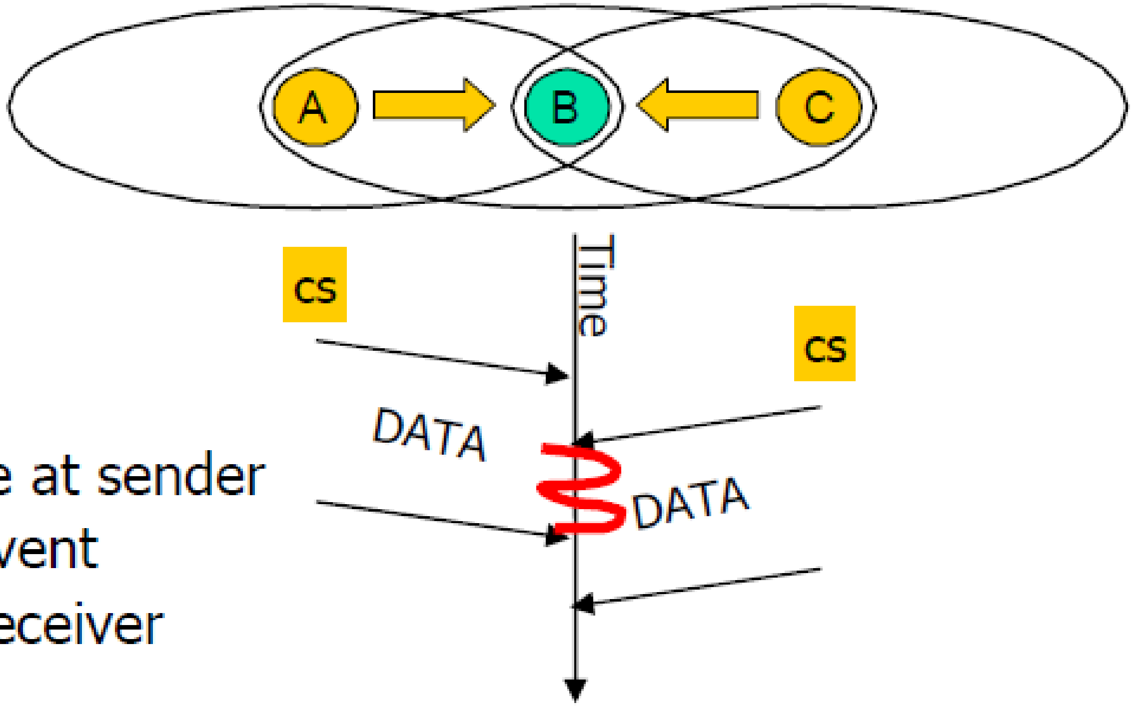
- Physical Layer for Wireless – Overview
- **MAC Layer for Wireless - Overview**
- IEEE 802.15.4 Protocol Overview
- Hardware implementation specs

MAC Layer
Fundamentals of (wireless) MAC Protocols
Introduction

- Main Task: it regulates the access of a number of nodes to a shared medium.
- Performance Requirements: delay, throughput, low overhead, fairness, and (for wireless) energy conservation.
- Overhead can result from per-packet (frame headers and trailers), collisions (→ retransmissions), or exchange of extra control packets.
- It inherits all the well-known problems of the underlying PHY layer, in this case using a Wireless medium; time-variable, high error rates, fading, path loss, attenuation, etc.

MAC Layer
Fundamentals of (wireless) MAC Protocols
Hidden-terminal problem

A and B are out of range

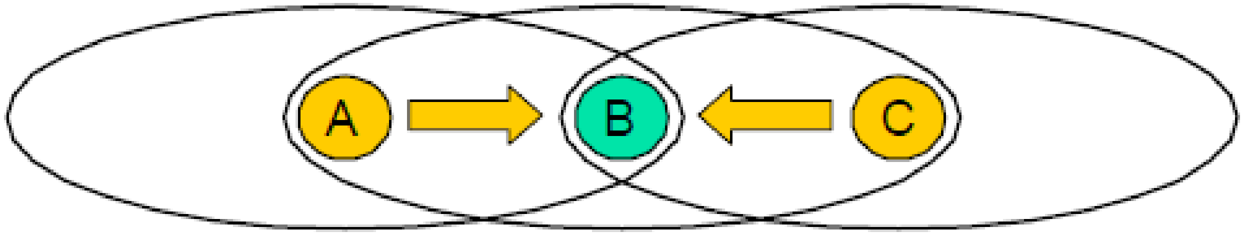


Carrier sense at sender may not prevent collision at receiver

MAC Layer

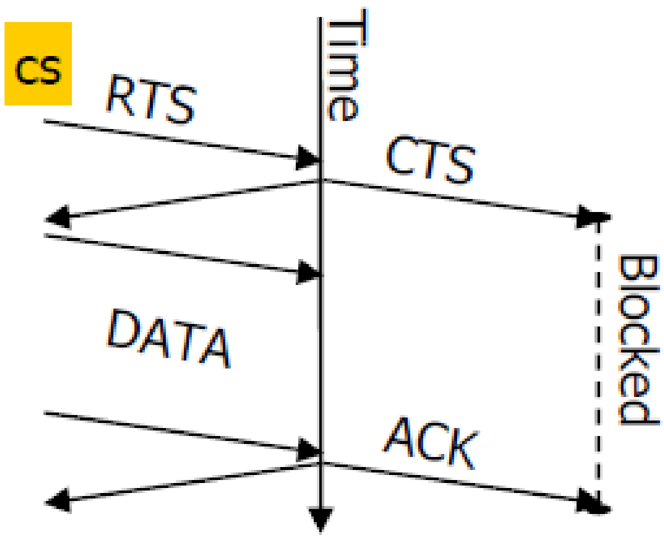
Fundamentals of (wireless) MAC Protocols

Hidden-terminal problem (solution)

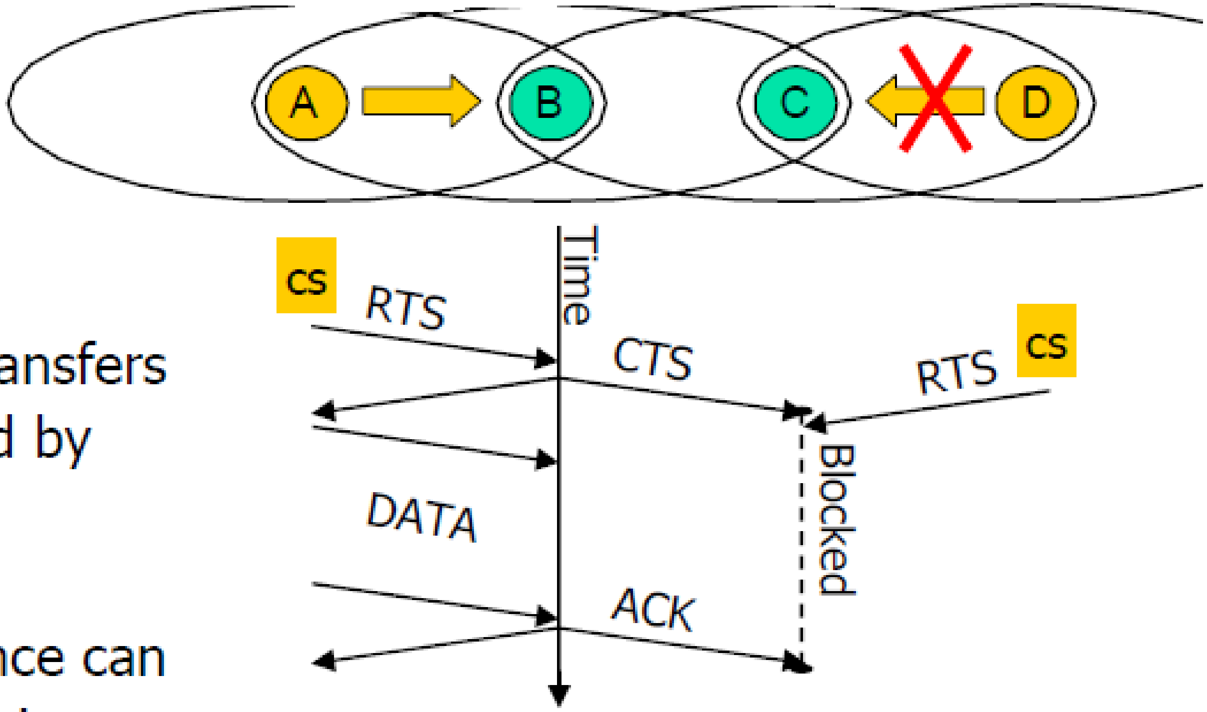


MACA:

- Request To Send
- Clear To Send
- DATA
- Acknowledge



MAC Layer
Fundamentals of (wireless) MAC Protocols
Exposed-terminal problem



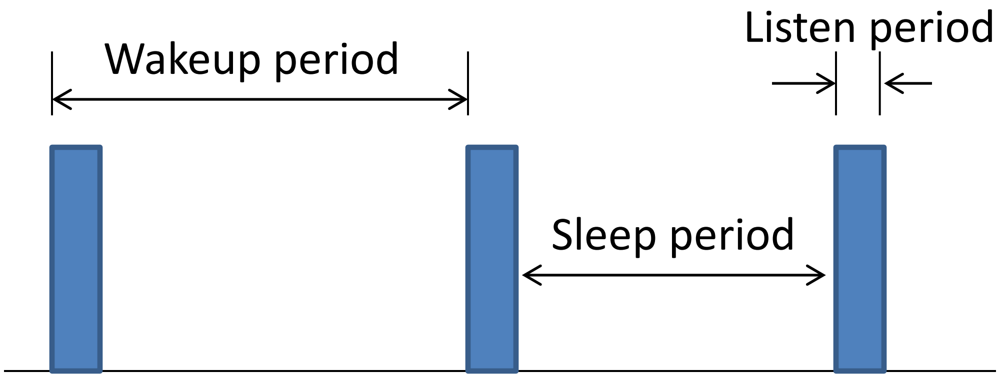
Parallel CSMA transfers are synchronized by CSMA/CA

Collision avoidance can be too restrictive!

MAC Layer
IEEE 802.15.4 MAC Overview
Energy saving requirements in wireless MAC protocols

- Transceivers can be in one of the four states: transmitting, receiving, idling, or sleeping.
- Energy problems:
  - Collision
  - Overhearing
  - Protocol overhead (per-packet or control frames)
  - Idle listening

MAC Layer
IEEE 802.15.4 MAC Overview
Energy savings approach

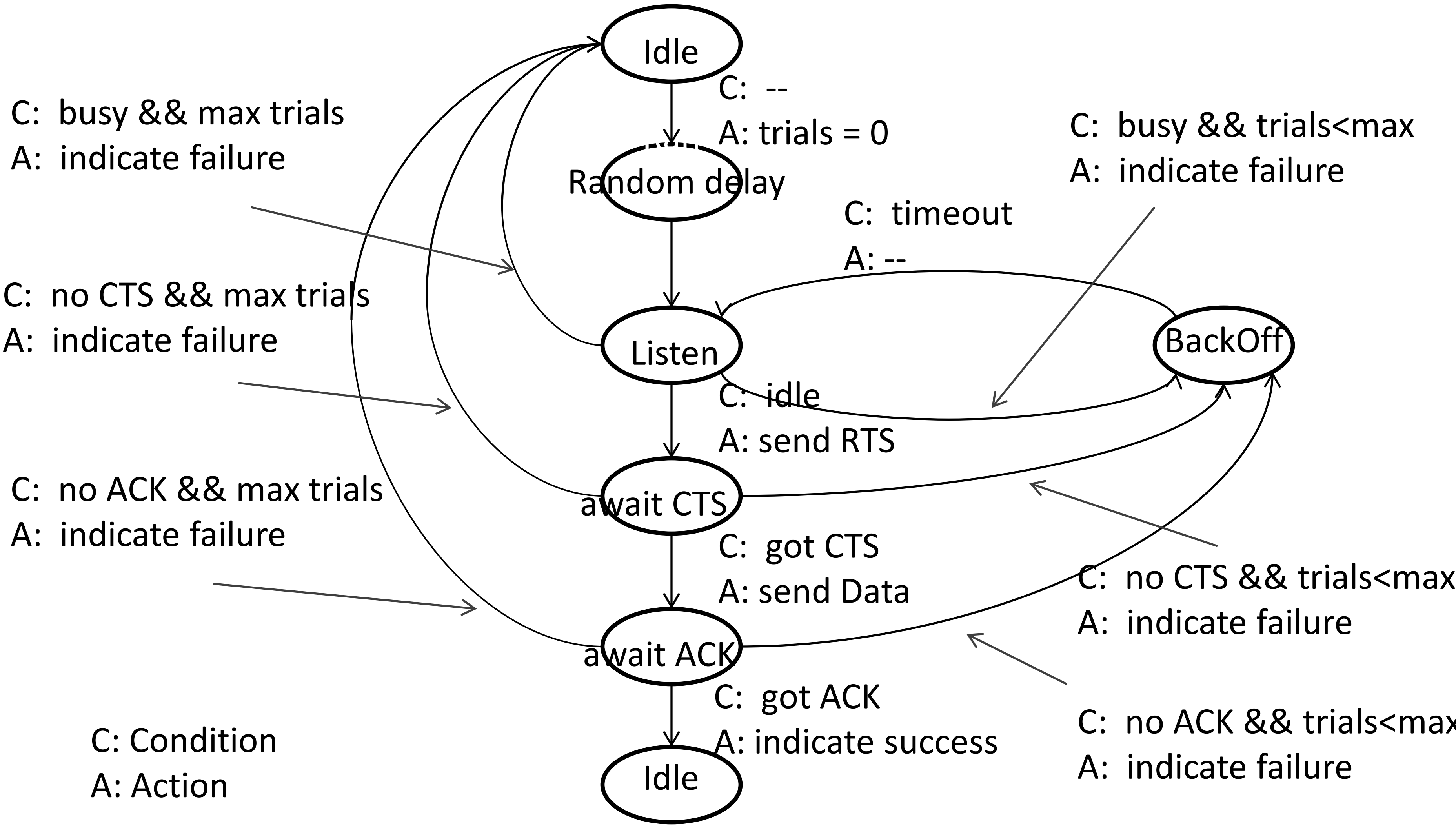


MAC Layer
(wireless) MAC Protocols
Different Approaches

- Common approaches:
  - Contention-based protocols
  - Scheduled-based protocols

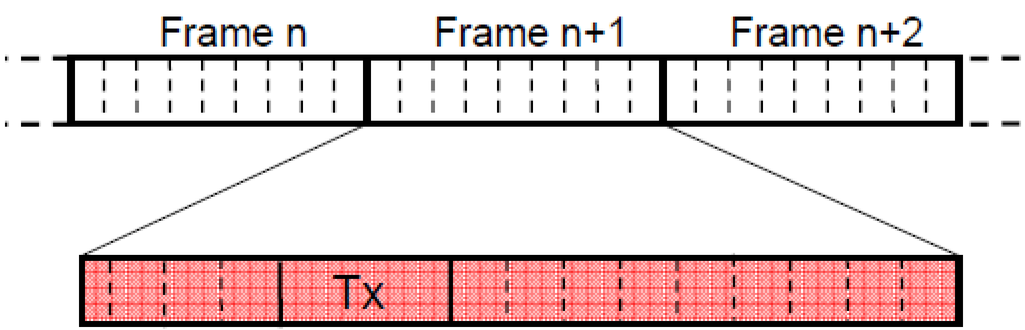
- Less used approaches:
  - Frequency division
  - Code division

MAC Layer
Contention-based protocols
CSMA (Carrier Sense Multiple Access)



MAC Layer
Schedule-based protocol
Overview

- Communication is scheduled in advance
- No contention
- No overhearing
- Time is divided into slotted frames (TDMA)
- Dedicated slot for transmission (no contention)
- Low power period when no transmission is
- expected



IEEE 802.15.4 standard

Agenda

- Physical Layer for Wireless – Overview
- MAC Layer for Wireless - Overview
- **IEEE 802.15.4 Protocol Overview**
- Hardware implementation specs

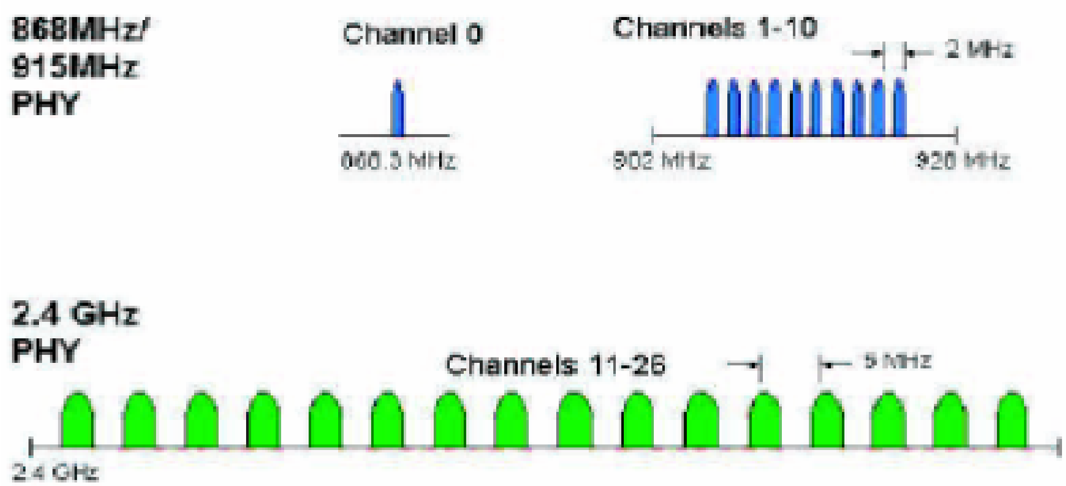
IEEE 802.15.4 standard

Introduction

- Released by IEEE in October 2003. Revisions in 2006, 2007, and 2009.
- It covers the PHY and MAC layers of low-rate WPAN.
- It's targeted for WSN, Home Automation, Home Networking, etc.
- Used by Zigbee (it adds Network construction, security and app. Services).
- Targeted Application Requirements:
  - Low-to-medium bit rates (up to few hundreds of kbps)
  - Moderate delays
  - Maximize energy savings

IEEE 802.15.4 standard
PHY Layer
Introduction

Communication over 26 channel in 3 ISM band



DSSS modulation:

- B-PSK: 20 kb/s (868MHz), 40kb/s(915MHz)
- Q-PSK: 250 kb/s (2.4GHz)

(The MAC protocol uses only one channel at a time)

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MAC Layer

Overview

- 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
- Security

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MAC Layer
Device Classes

- 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

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MAC Layer

Definitions

- 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.

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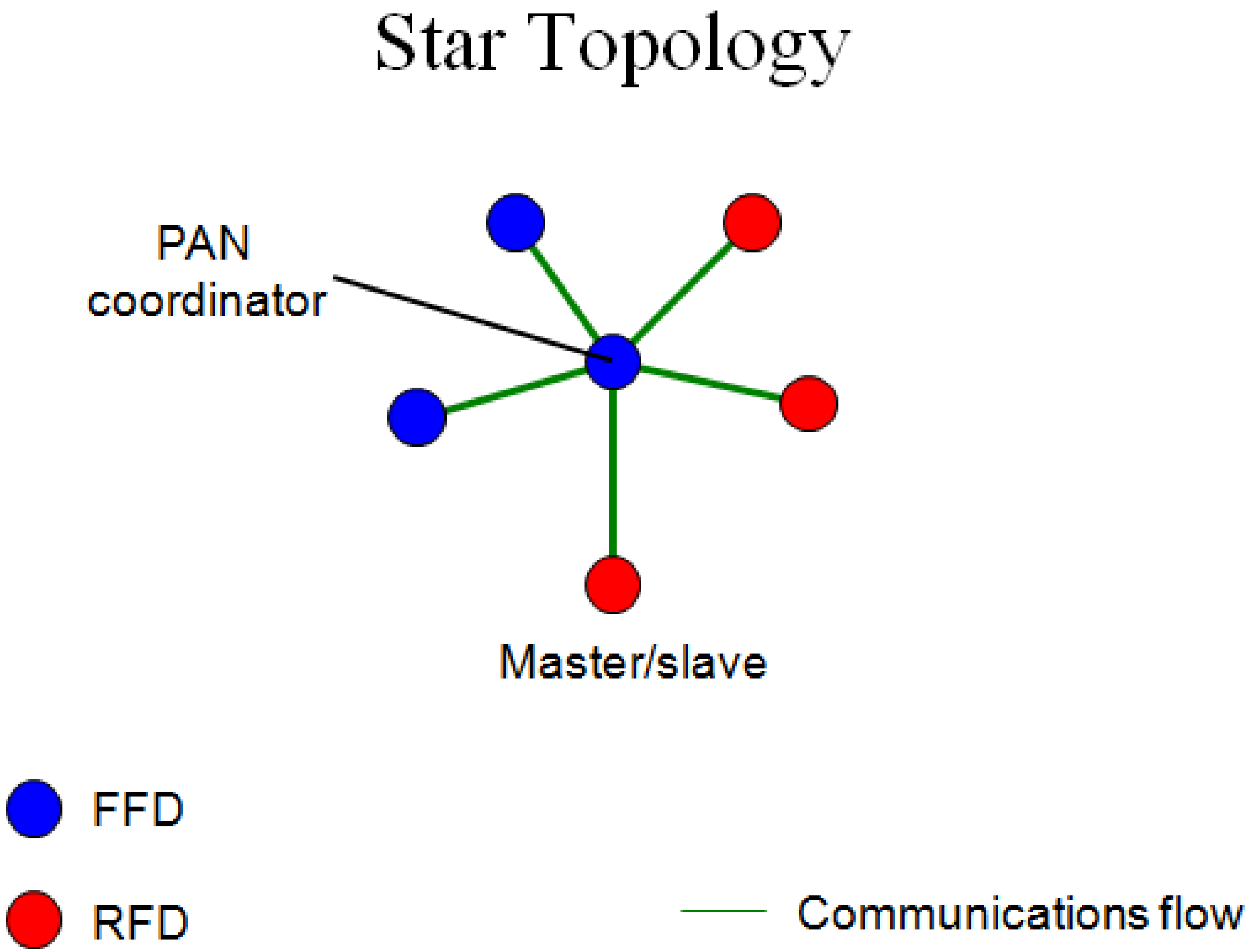
MAC Layer

Star topology



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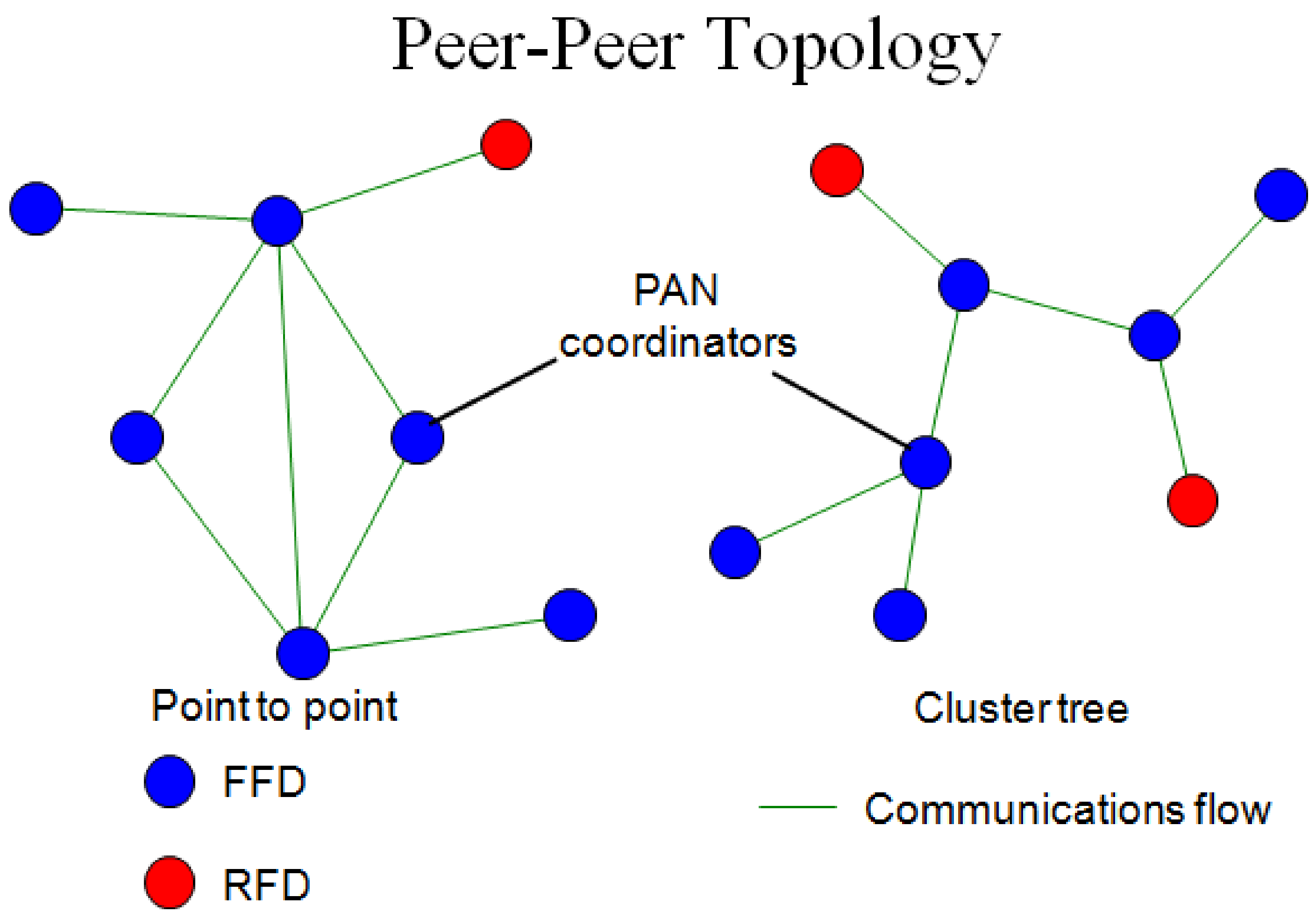
MAC Layer

Peer-to-Peer topology



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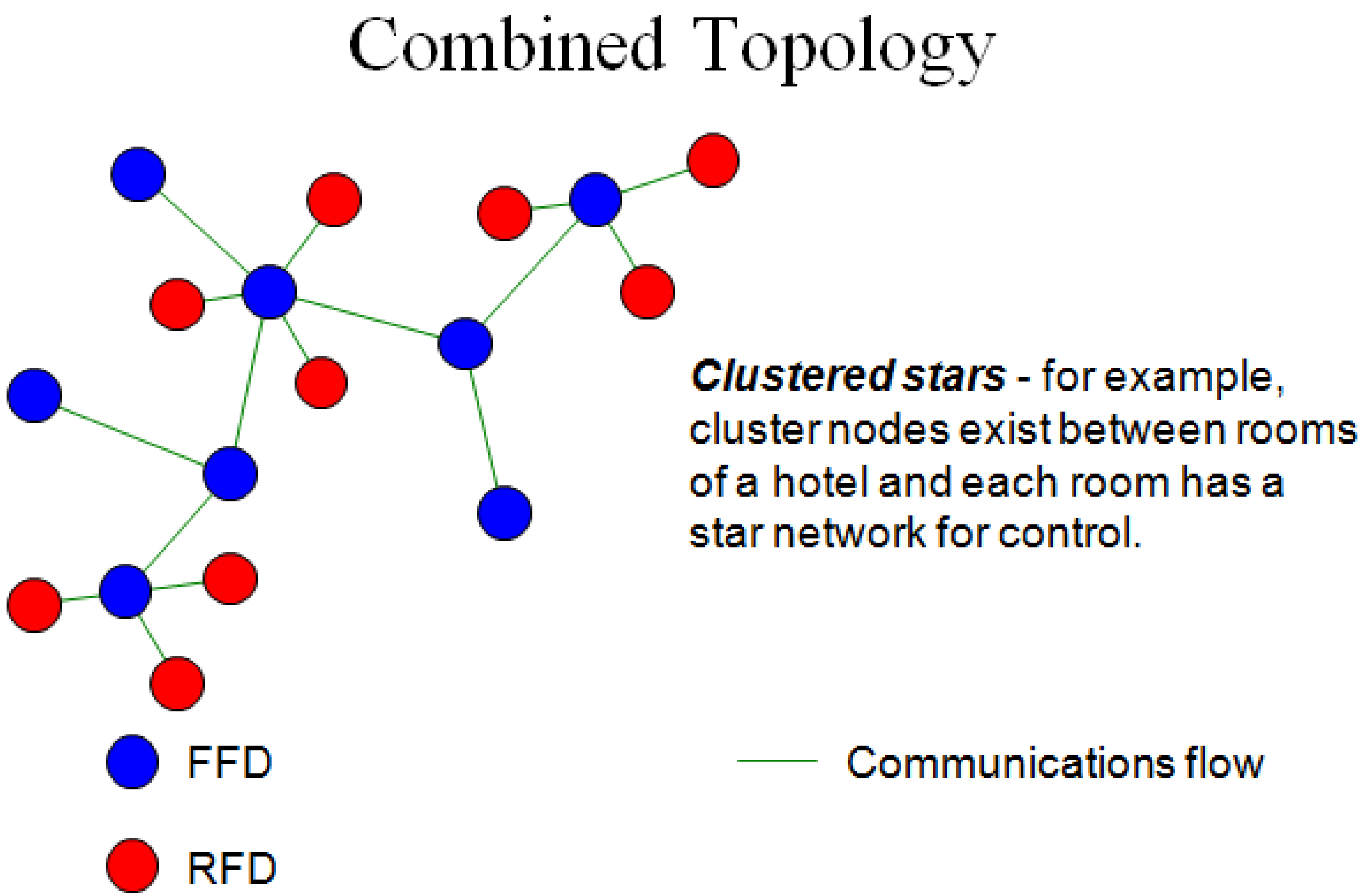
MAC Layer

Combined topology



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MAC Layer

Nodes Associations

- A Device must be associated with a Coordinator (FFD) (forming a Star Network)
- Coordinators can operate in a peer-to-peer fashion, and multiple Coordinators can form a PAN.
- The PAN is identified with a 16-bit PAN Identifier.
- One of the Coordinators is designated as a PAN Coordinator.

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MAC Layer

Coordinator Tasks

- It manages a list of associated devices
- It allocates short addresses to its devices (All IEEE 802.15.4 nodes have a 64-bit device address. When device associates with a coordinator, it may request a 16-bit (short) address for subsequent communications between device and coordinator)
- In Beaconed mode, it regularly transmit Beacon frames.
- It exchanges data packets with devices and with peer coordinators.

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MAC Layer

Addressing

- All devices have 64 bit IEEE addresses
- Short addresses can be allocated
- Addressing modes:
  - Network + device identifier (star)
  - Source/destination identifier (peer-peer)

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MAC Layer
Coordinator-Device communication (Beaconed mode)

- The Coordinator of a Star Network operating in Beaconed mode organizes channel access and data transfer using a Superframe structure.
- The Coordinator starts each Superframe by sending a frame beacon packet.
- All superframes have the same length
- The frame beacon includes a superframe specification (details).
  - Superframe is divided into an Active period and Inactive period (optional)
  - Active period is subdivided into 16 time slots. First slot is beacon frame. Remaining slots conforms the Contention Access Period (CAP) followed by the Guaranteed Time Slot (GTS) – max. seven.
- Coordinators are active during the Active period.
- Devices are active only in GTS (during the assigned slot)
- Devices are active during CAP, only if they have something to transmit.

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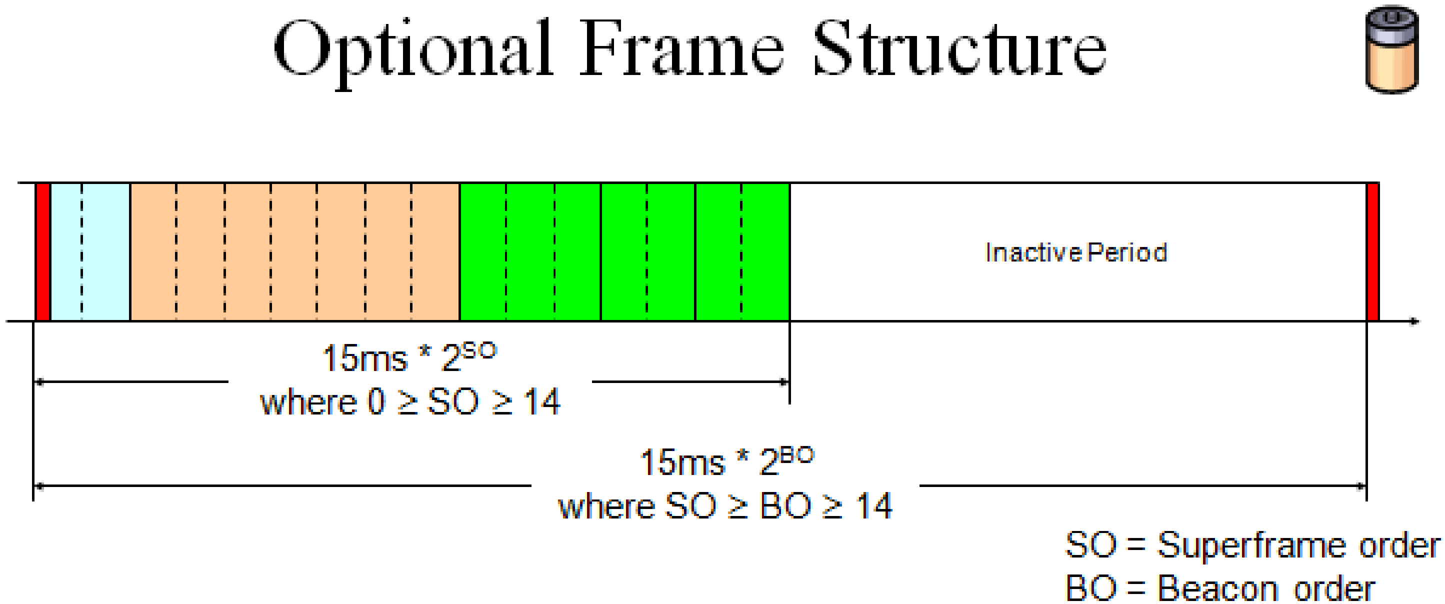
MAC Layer
Frame Structure



- Superframe may have inactive period

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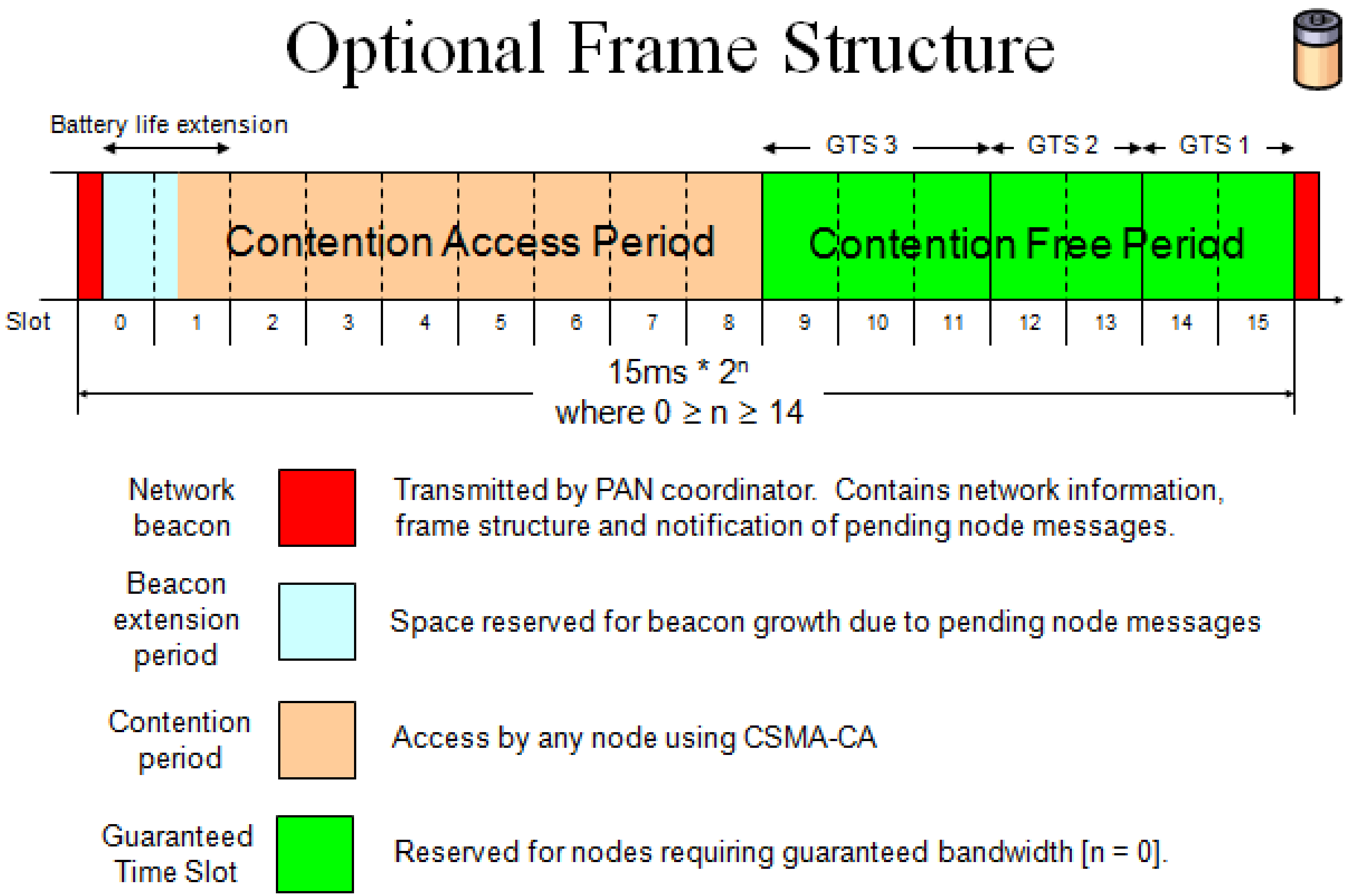
MAC Layer
Frame Structure



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MAC Layer

GTS management

- Devices send Request packets during the CAP (including how many time slots are desired and a flag indicating transmit or receive slot)
- Coordinator answers the request in two steps:
  - A) It sends an ACK for the request.
  - B1) If it has sufficient resources to allocate the request, it inserts an appropriate GTS descriptor in the next beacon frame. This descriptor specifies the short address of the requesting device and the number of slots and position in the GTS area, the device can use for data exchange.
  - B2) If no resources are available, the Coordinator can allocate less slots or no slots at all (indicated by an invalid time slot).
- Once the Device finish with the data exchange, it should deallocate the allocated slots, or the Coordinator can deallocate them if needed (low resources, higher priorities, etc) or discover the device is not longer using the assigned slots.

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MAC Layer
Data transfer using CAP

- If the full transaction (data packet, acknowledge and InterFrame Spaces) doesn't fit in the allocated slots, the CAP area need to be used.
- Devices transmit data using slotted CSMA (next slide).
- If a Coordinator has data to transmit for a Device, it includes the Device address in the Pending Address Field of the Beacon frame. This way, the addressed Device knows there is data for it and generates a Data request packet during the CAP using the slotted CSMA.

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MAC Layer

Slotted CSMA-CA protocol

- Since there is no RTS/CTS mechanism, a BackOff period (random delays) is used to reduce the probability of collissions (CSMA with Collision Avoidance).
- The Time Slots making up the CAP are subdivided into smaller time slots, called BackOff Periods (length of 20 symbol times).

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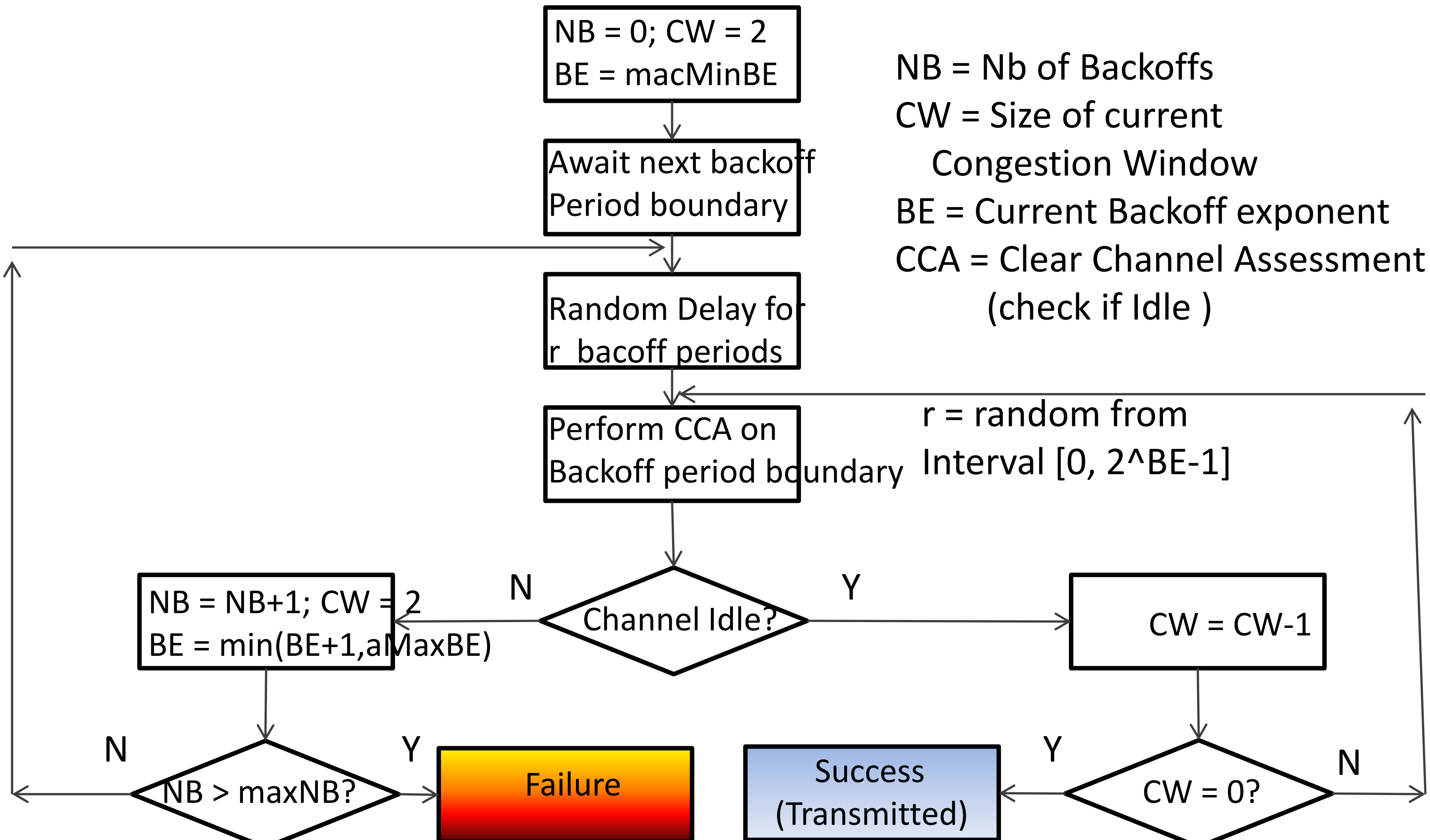
MAC Layer

Slotted CSMA-CA protocol Algorithm



NB = Nb of Backoffs
CW = Size of current Congestion Window
BE = Current Backoff exponent
CCA = Clear Channel Assessment (check if Idle)

r = random from Interval [0, 2^BE-1]

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MAC Layer

Non-Beaconed mode

- The Coordinator does not send beacon frames nor is there any GTS mechanism (lack of sync. using the beacon).
- Since there is no sync., Devices transmit packets using unslotted CSMA-CA.
- Devices can be switched off following their own sleep schedule, but Coordinators need to be active all the time.

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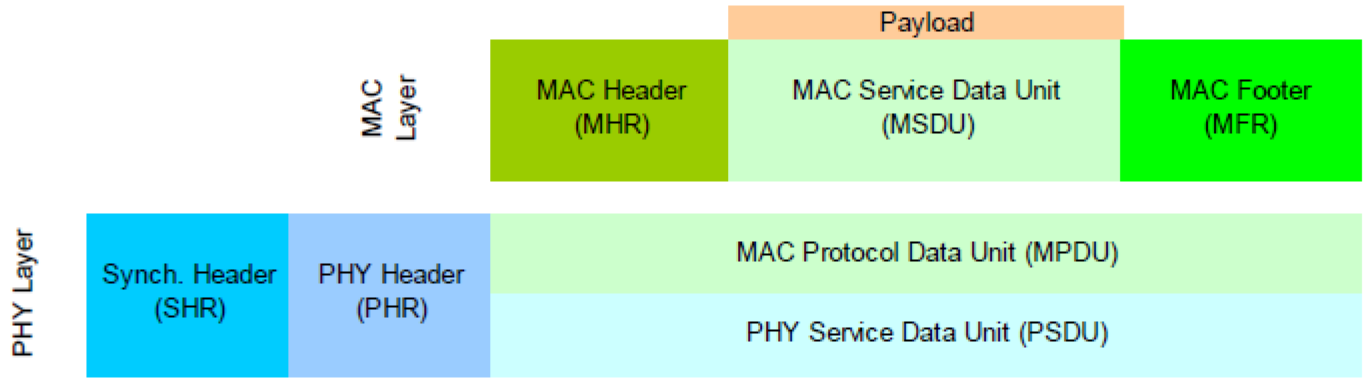
MAC Layer

General Frame Structure



4 Types of MAC Frames:

- Data Frame
- Beacon Frame
- Acknowledgment Frame
- MAC Command Frame

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MAC Layer
General MAC Frame Format

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	Sequrity enabled	Frame pending	Ack. Req.	Intra PAN	Reserved	Dest. addressing mode	Reserved	Source addressing mode

Frame control field

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MAC Layer

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

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MAC Layer

MAC 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

IEEE 802.15.4 standard
MAC Layer
Data and ACK Frame Format

Data Frame Format

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 Format

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

IEEE 802.15.4 standard

Agenda

- Physical Layer for Wireless – Overview
- MAC Layer for Wireless - Overview
- IEEE 802.15.4 Protocol Overview
- **Hardware implementation specs**

Hardware Implementation

TI CC2520 DataSheet

Key Features

TEXAS INSTRUMENTS

CC2520 DATASHEET
2.4 GHZ IEEE 802.15.4/ZIGBEE® RF TRANSCEIVER
SWRS068 – DECEMBER 2007

APPLICATIONS
- IEEE 802.15.4 systems
- ZigBee® systems
- Industrial monitoring and control
- Home and building automation
- Automatic Meter Reading
- Low-power wireless sensor networks
- Set-top boxes and remote controls
- Consumer electronics

KEY FEATURES
- State-of-the-art selectivity/co-existence
  Adjacent channel rejection: 49 dB
  Alternate channel rejection: 54 dB
- Excellent link budget (103dB)
  400 m Line-of-sight range
- Extended temp range (-40 to +125°C)
- Wide supply range: 1.8 V – 3.8 V
- Extensive IEEE 802.15.4 MAC hardware support to offload the microcontroller
- AES-128 security module
- CC2420 interface compatibility mode

Low Power
- RX (receiving frame, -50 dBm) 18.5 mA
- TX 33.6 mA @ +5 dBm
- TX 25.8 mA @ 0 dBm
- <1µA in power down

Radio
- IEEE 802.15.4 compliant DSSS baseband modem with 250 kbps data rate
- Excellent receiver sensitivity (-98 dBm)
- Programmable output power up to +5 dBm
- RF frequency range 2394-2507 MHz
- Suitable for systems targeting compliance with worldwide radio frequency regulations: ETSI EN 300 328 and EN 300 440 class 2 (Europe), FCC CFR47 Part 15 (US) and ARIB STD-T66 (Japan)

Microcontroller Support
- Digital RSSI/LQI support
- Automatic clear channel assessment for CSMA/CA
- Automatic CRC
- 768 bytes RAM for flexible buffering and security processing
- Fully supported MAC security
- 4 wire SPI
- 6 configurable IO pins
- Interrupt generator
- Frame filtering and processing engine
- Random number generator

Development Tools
- Reference design
- IEEE 802.15.4 MAC software

Hardware Implementation

TI CC2520 DataSheet

Description

DESCRIPTION

The CC2520 is TI's second generation ZigBee® / IEEE 802.15.4 RF transceiver for the 2.4 GHz unlicensed ISM band. This chip enables industrial grade applications by offering state-of-the-art selectivity/co-existence, excellent link budget, operation up to 125°C and low voltage operation.

In addition, the CC2520 provides extensive hardware support for frame handling, data buffering, burst transmissions, data encryption, data authentication, clear channel assessment, link quality indication and frame timing information. These features reduce the load on the host controller.

In a typical system, the CC2520 will be used together with a microcontroller and a few additional passive components.

QFN28 (RHD) PACKAGE TOP VIEW