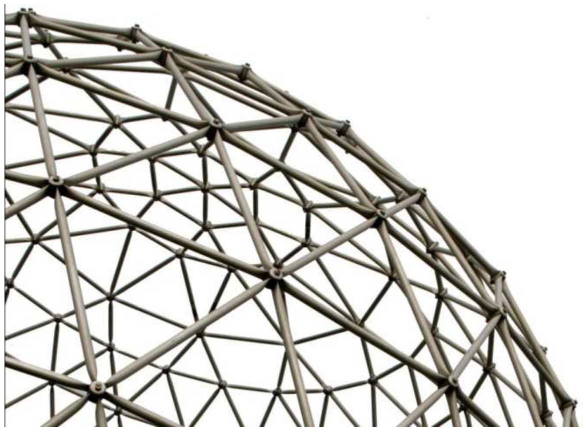
Module: Internet of Things

Lecture 3: Hardware Platform



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Overview

– Sensors & Actuators

– Node Architecture

– Communication Architecture

Sensors & Actuators

Sensors Characteristics

- Sensors:
  - They are mainly input components in IoT
  - They are devices that receive a stimulus and responds with an electrical signal
  - Basically three types:
    - Passive, omnidirectional (e.g. mic)
    - Passive, narrow-beam sensor (e.g. PIR)
    - Active sensors (e.g. sonar, radar, etc.)
  - Unit of measurements:
    - SI: modernized metric system.

Quantity	**Name**	**Symbol**
Length	Meter	m
Time	Second	s
Electric current	Ampere	A
Luminous intensity	Candela	cd
…		

Transfer Function

- A transfer function for a sensor: a mathematical function representing the input-output relation.
  - Input: a physical measured parameter
  - Output: usually an electrical output signal.
- It describes the system response of a sensor.

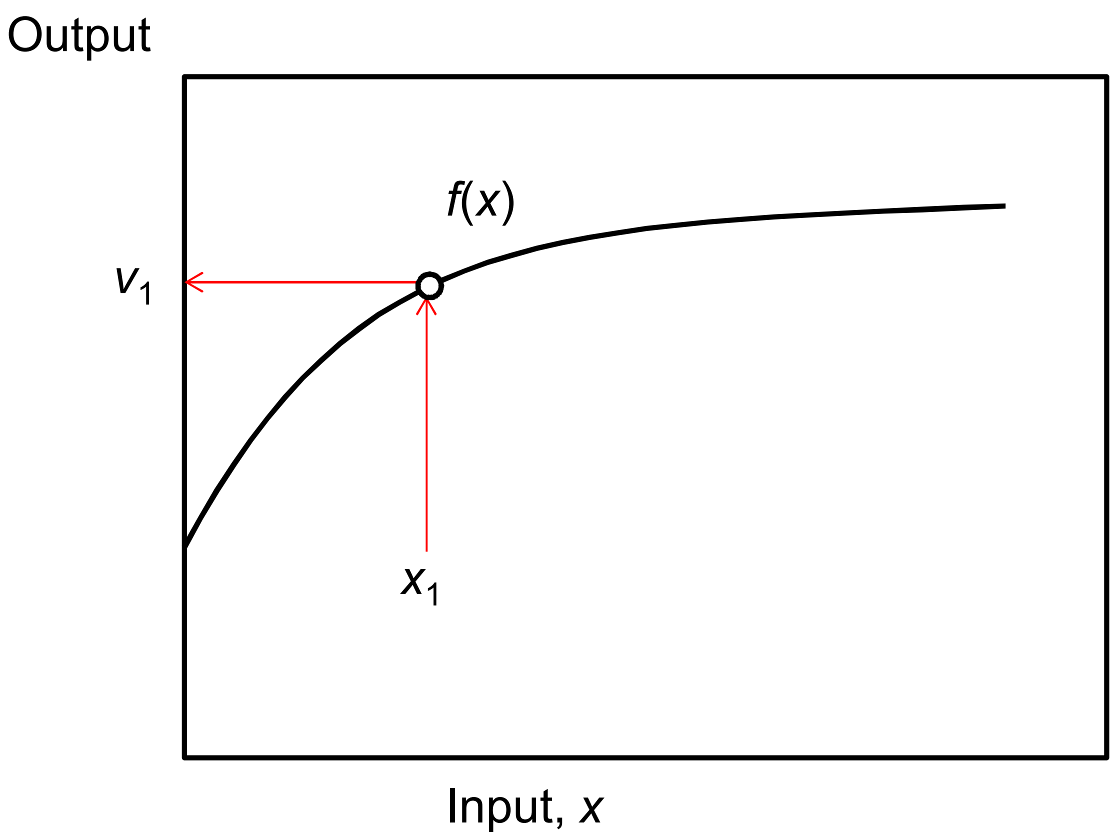
- The simplest form of transfer function is a linear function which can be described as follows.

$$S = a + bx$$

where x is the input, b is the slope (and sometimes called sensitivity), and a is the offset (or the output when the input is zero).

Transfer Function

– An example:



– Inverse transfer function: to tell the physical measured parameter based on sensor output.

Transfer Function: Linear/Nonlinear

– Linear:
  – It can be described by a straight line:

$$S = a + bx$$

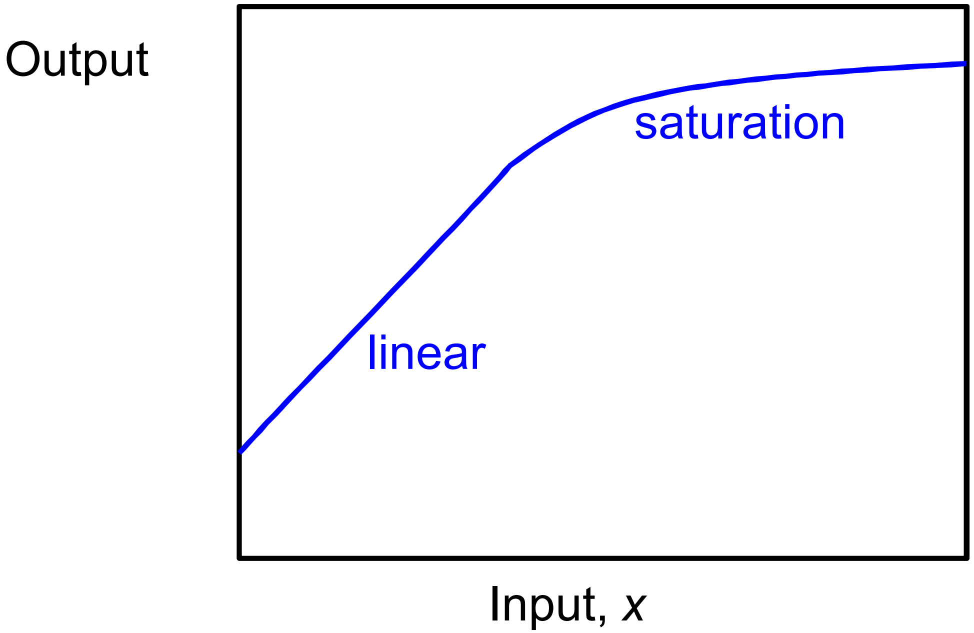
  – Hardly any sensor produces linear transfer function, there is always some nonlinearity in the function.

– Nonlinear:
  – Any response that is not linear
  – Appropriate functions should be utilized to describe the response (e.g. multiple linear functions, polynomial function, exponential function, etc)

Transfer Function

- Multiple Inputs
  - Some sensors may depend on multiple inputs
    - e.g. humidity sensor (two inputs: relative humidity and temperature)

- Saturation
  - The output becomes flat at some levels of input

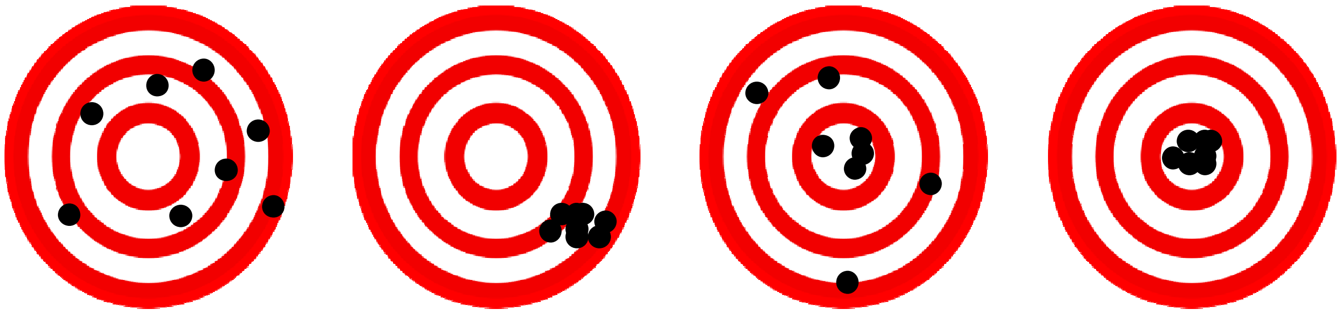


Transfer Function

– Resolution
  – It describe the smallest increment of stimulus
  – Outputs change in small steps

– Accuracy
  – It describes how close the measurement is to the true value

– Precision or Repeatability
  – It describes the difference in results when measurements are taken repeatedly under the same conditions



Accuracy:	Low	Low	High	High
Repeatability:	Low	High	Low	High

Sensors Technology
A Quick Overview

Projected capacitive touchscreen.

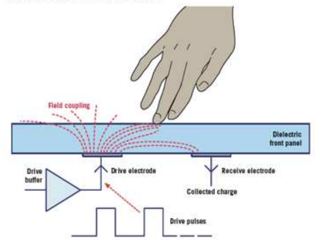
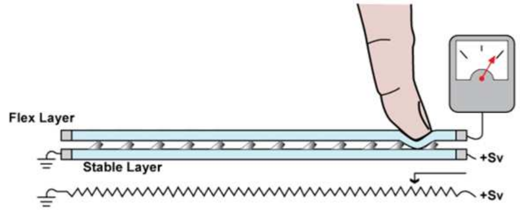


Figure 1

- Capacitive
  - A change in capacitance with a change in environment
    - Can detect liquids and objects based on their dielectric constant
    - Can take human body capacitance as input
  - For detection of displacement, humidity, acceleration, human contact, etc.



- Resistive
  - A change in resistance with a change in environment
    - Physical changes include light, force, heat, magnetic field, etc.
  - For detection of light, force, heat, etc.
  - Applications include camera, street lights, music instruments, weight sensing, touch screen, etc.

Sensors Technology
A Quick Overview

– Magnetic (passive)
  – There are several approaches for magnetic sensing, eg. Hall effect sensor, magneto-diode, magneto-transistor, etc.
  – Generally, they detect magnetic fields or their alteration by ferromagnetic objects.
  – For measuring of rotary movement, Earth's magnetic field, etc.

– Inductive (active)
  – A change in the amplitude of an emitted high frequency electromagnetic field the oscillations.
  – For detection of metallic object and different metals
  – Common in vehicle detection

Sensors Technology
A Quick Overview

- Thermoelectric
  - A creation of voltage when there is a different temperature on each side of an object
  - For measurement of temperature

- Pyroelectric
  - A temporary voltage generated from a certain material when it is heated or cooled
  - For human/animal motion detection, flame detection, NDIR (Non Dispersive IR) gas analysis, etc.
  - Common in PIR (Passive InfraRed) sensors

Sensors Technology
A Quick Overview

- Sound level
  - A generation of electrical voltage signals with vibration of air
  - Two popular approaches: inductive (dynamic microphone) and capacitive (condenser microphone)
  - Common sensing application: Sound meter

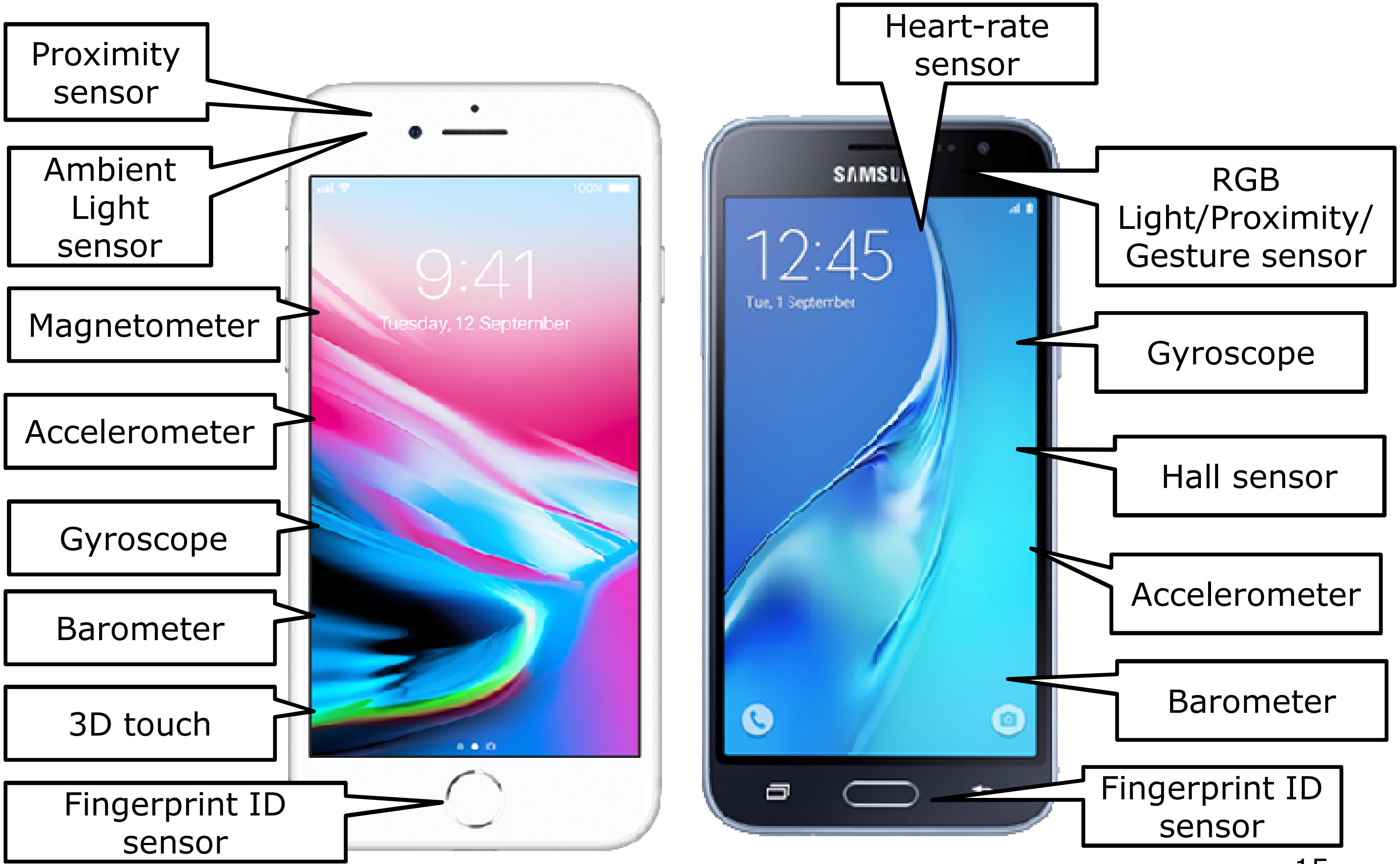
Sensors Technology
A Quick Overview

– Other sensing technologies

  – Electromechanical sensors
    – Involving of mechanical devices.
    – Some examples:
      – Fluid flow measurement (e.g. mechanical flow meters), Microelectromechanical systems (e.g. MEMS gyroscopes), etc.

  – Electrochemical sensors
    – Involving interaction between electricity and chemistry.
    – Some examples:
      – CO detector, pH meter, etc.

Sensors in Modern Smart Phones

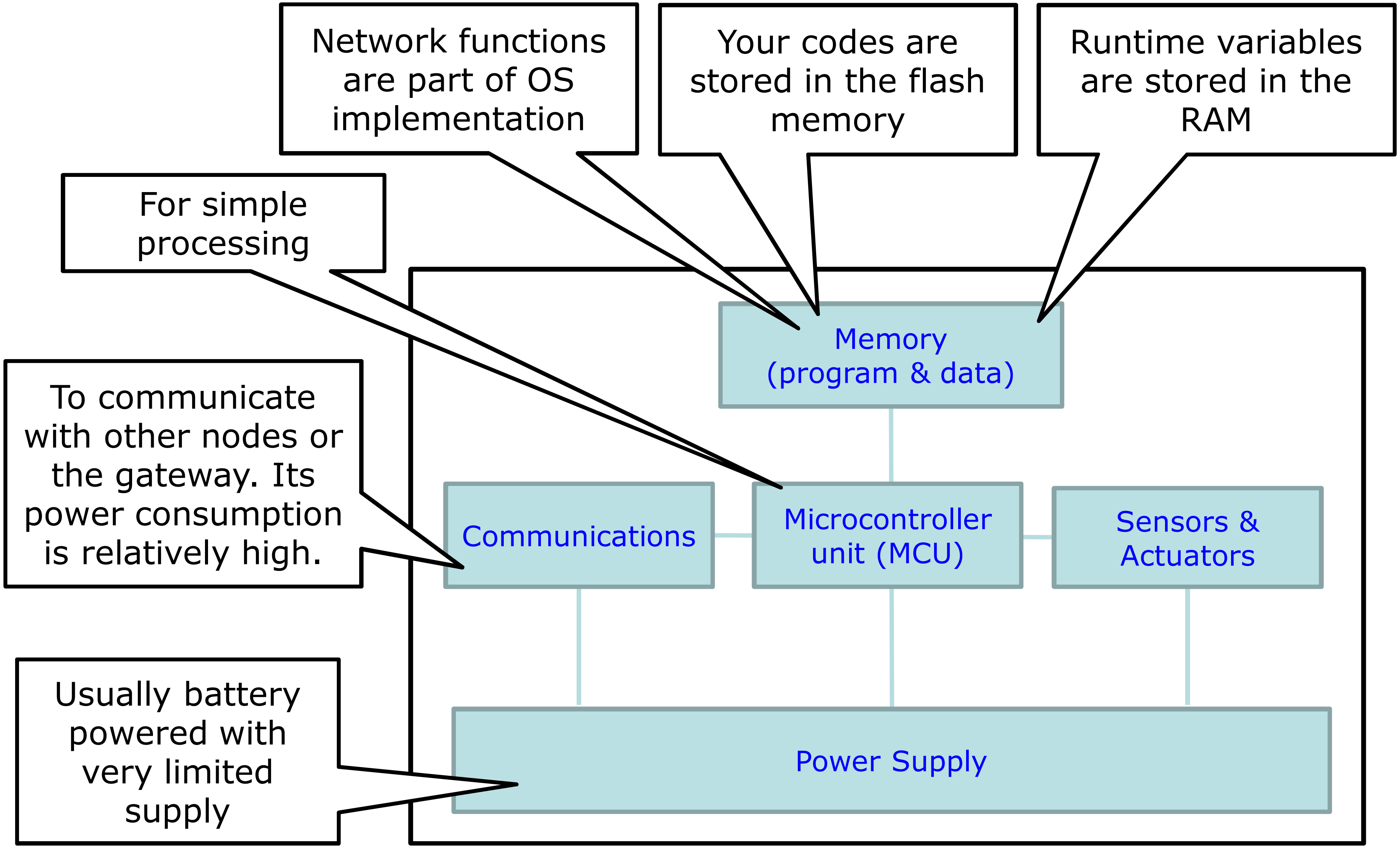


Actuators

- They are mainly output components
- Generally 4 types:
  - Hydraulic: use hydraulic power, powerful but slow
  - Pneumatic: use compressed air, rapid delivery
  - Electric: use electricity, versatile ←for IoT
  - Mechanical: use other mechanical energy
- They alter the surrounding. Some examples:
  - Adding light, heat, sound, moisture, etc.
  - Moving objects
  - Displaying messages
  - and others…

Node Architecture

Hardware Components



XM1000: Processor and Memory

Item	Specification	Description
Processor		
Processor Model	TI MSP430F2618	Texas Instruments MSP430 family 16-Bit RISC Architecture 62.5-ns Instruction Cycle Time
Memory	116KB 8KB 1MB	Program flash Data RAM External Flash (ST® M25P80)
ADC	12bit resolution	8 channels
Interfaces	UART, SPI, I2C USB	Serial Interfaces External System Interface (FTI® FT232BM)

Very limited resources

XM1000: Sensors

Sensors		
Light 1	Hamamatsu® S1087	Visible Range (560 nm peak sensitivity wavelength)
Light 2	Hamamatsu® S1087-01	Visible & Infrared Range (960 nm peak sensitivity wavelength)
Temperature & Humidity	Sensirion® SHT11	Temperature Range: -40 ~ 123.8 ºC Temperature Resolution: : ± 0.01(typical) Temperature Accuracy: ± 0.4 ºC (typical) Humidity Range: 0 ~ 100% RH Humidity Resolution: 0.05 (typical) Humidity Accuracy: ± 3 %RH (typical)

Light, Humidity, Temperature

Block Diagram (from the datasheet)

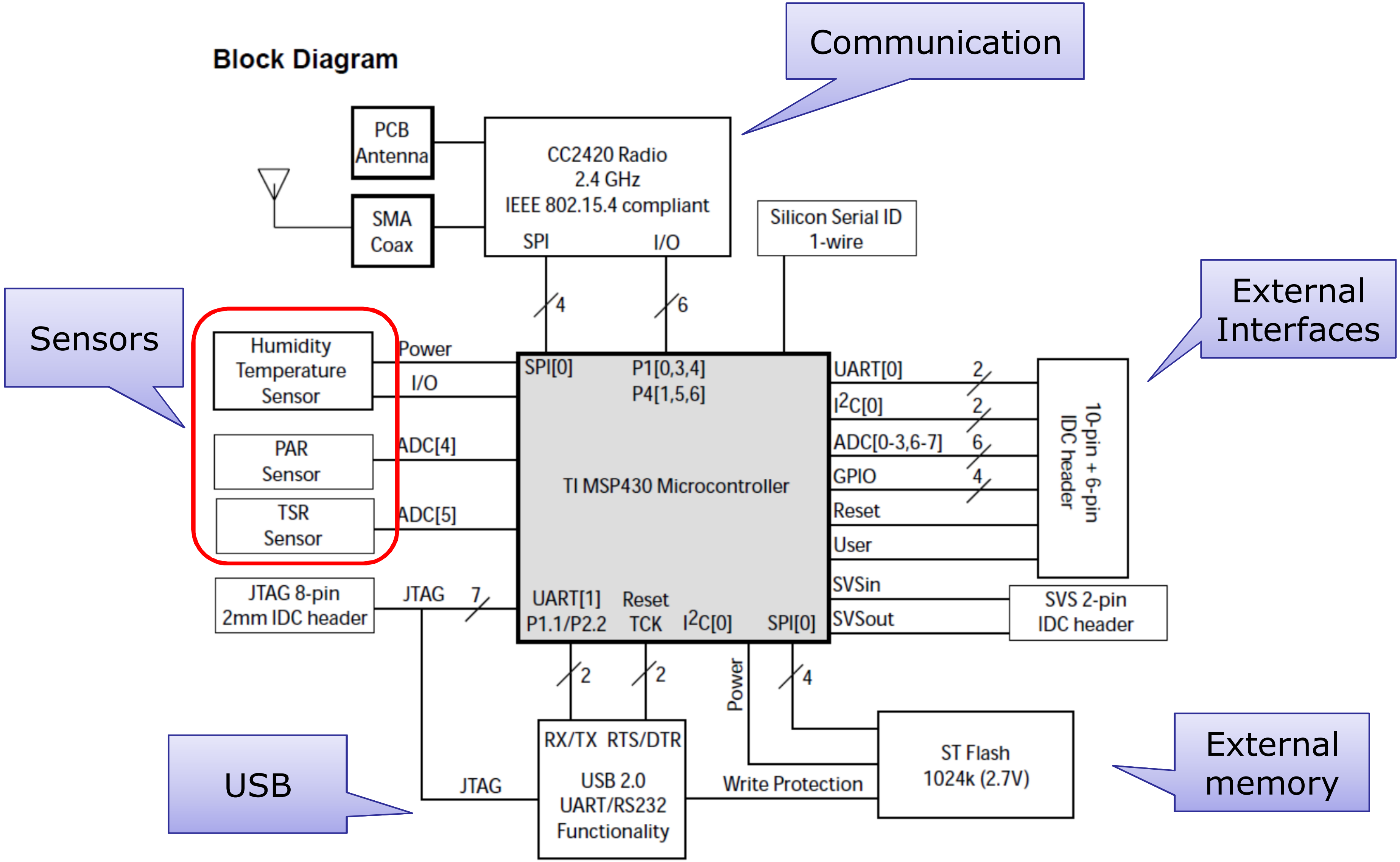
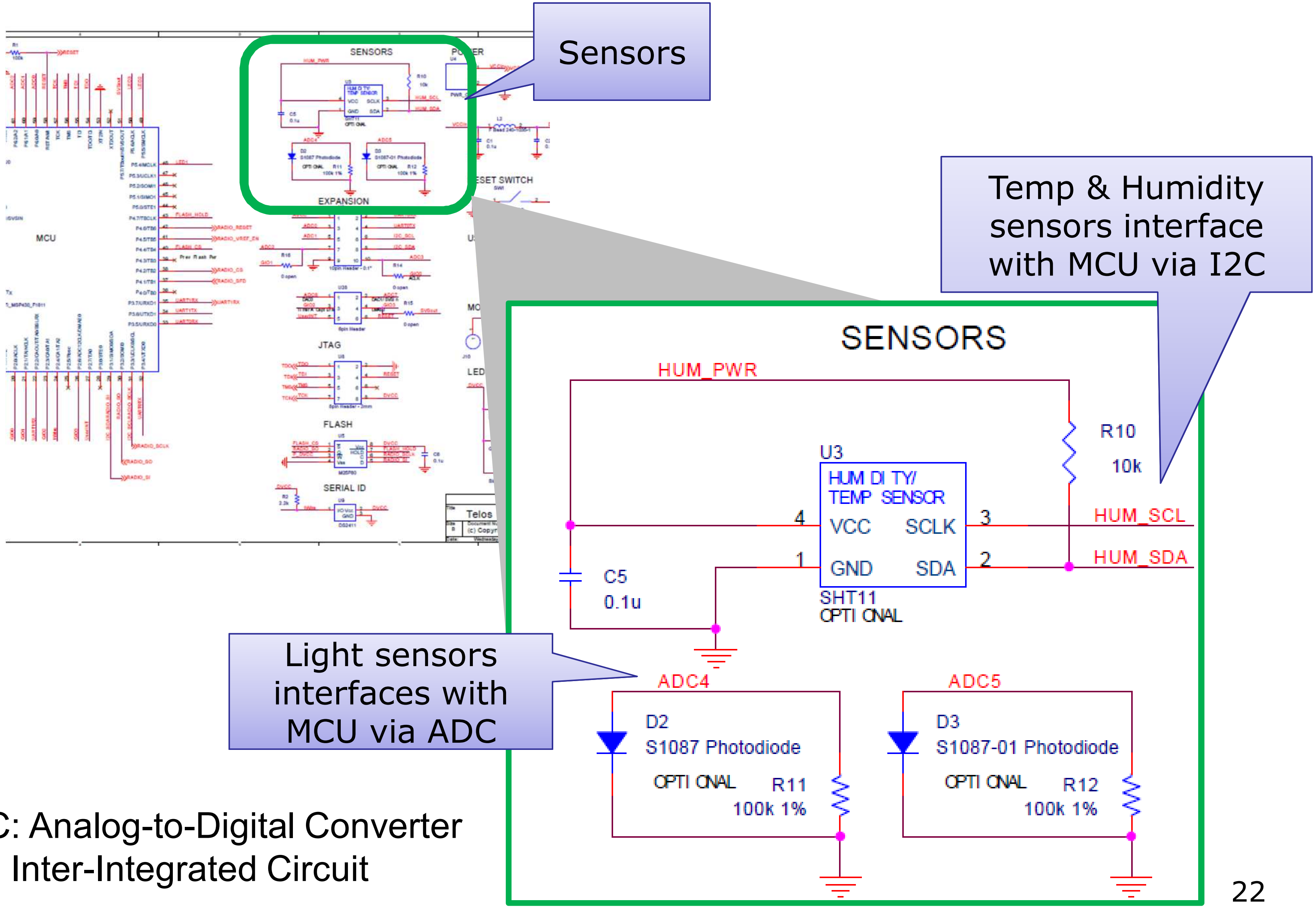


Figure 3 : Functional Block Diagram of the Telos Module, its components, and buses

Schematic (from the datasheet)



ADC: Analog-to-Digital Converter
I2C: Inter-Integrated Circuit

XM1000: Sensors

Sensor Performance

Relative Humidity

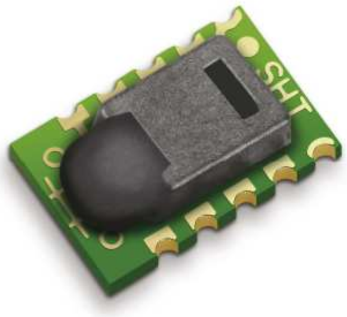
Parameter	Condition	min	typ	max	Units
Resolution [1]		0.4	0.05	0.05	%RH
		8	12	12	bit
Accuracy [2] SHT10	typical		±4.5		%RH
	maximal	see Figure 2			
Accuracy [2] SHT11	typical		±3.0		%RH
	maximal	see Figure 2			
Accuracy [2] SHT15	typical		±2.0		%RH
	maximal	see Figure 2			
Repeatability			±0.1		%RH
Hysteresis			±1		%RH
Non-linearity	linearized		<<1		%RH
Response time [3]	τ (63%)		8		s
Operating Range		0		100	%RH
Long term drift [4]	normal		< 0.5		%RH/yr

Temperature

Parameter	Condition	min	typ	max	Units
Resolution [1]		0.04	0.01	0.01	°C
		12	14	14	bit
Accuracy [2] SHT10	typical		±0.5		°C
	maximal	see Figure 3			
Accuracy [2] SHT11	typical		±0.4		°C
	maximal	see Figure 3			
Accuracy [2] SHT15	typical		±0.3		°C
	maximal	see Figure 3			
Repeatability			±0.1		°C
Operating Range		-40		123.8	°C
		-40		254.9	°F
Response Time [6]	τ (63%)	5		30	s
Long term drift			< 0.04		°C/yr

Electrical and General Items

Parameter	Condition	min	typ	max	Units
Source Voltage		2.4	3.3	5.5	V
Power Consumption [5]	sleep		2	5	µW
	measuring		3		mW
	average		90		µW
Communication	digital 2-wire interface, see Communication				
Storage	10 – 50°C (0 – 125°C peak), 20 – 60%RH				



Temperature Sensor – SHT11

Transfer function:
(given in the
Data sheet)

$$T = d_1 + d_2 \cdot SO_T$$

VDD	d_1 (°C)	d_1 (°F)
5V	-40.1	-40.2
4V	-39.8	-39.6
3.5V	-39.7	-39.5
3V	-39.6	-39.3
2.5V	-39.4	-38.9

SO_T	d_2 (°C)	d_2 (°F)
14bit	0.01	0.018
12bit	0.04	0.072

The sensor uses 14 bits

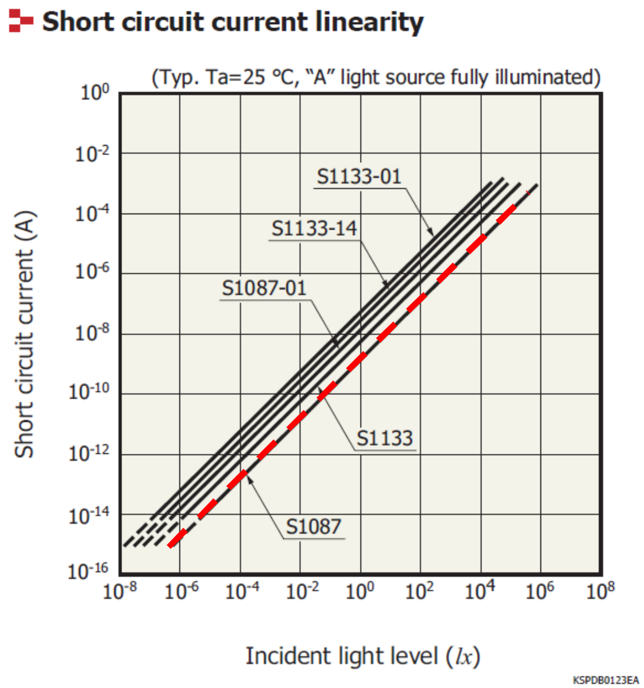
We use 3V

Table 8: Temperature conversion coefficients[15].

SO_T = reading (14-bit)
T = temperature (-39.6°C to 124.23°C)

Light Sensor – S1087

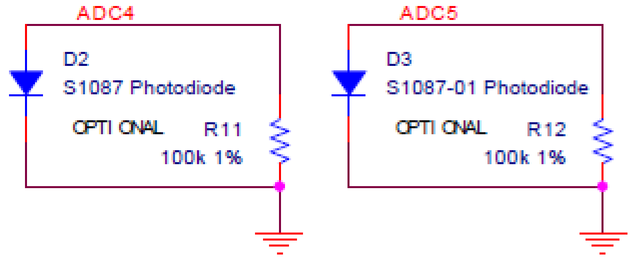
(see ./platform/xm1000/apps/sensors/sensorReading.c under contiki folder)



Relationship between light (L, in unit lx) and current (I in unit A):

$L = 0.625 \times 10^6 \times I \times 1000$

Circuits:



Based on Ohm's law:

$V = I \times R$

where R = 100k

and V is sent into 12-bit ADC.

Relationship between ADC value and V is: $ADC = \frac{V}{V_{ref}} \cdot 2^{12}$

where $V_{ref} = 1.5$ (given in the data sheet)

So, to determine the light level, we do:

```
float V_sensor = 1.5 * light_sensor.value(LIGHT_SENSOR_PHOTOSYNTHETIC)/4096;
float I = V_sensor/100000; // <- Ohm's law
float light_lx = 0.625*1e6*I*1000; // <- based on data sheet
```

XM1000: Communication Unit

Item	Specification	Description
Radio		
RF Chip	TI CC2420	IEEE 802.15.4 2.4GHz Wireless Module
Frequency Band	2.4GHz ~ 2.485GHz	IEEE 802.15.4 compliant
Sensitivity	-95dBm typ	Receive Sensitivity
Transfer Rate	250Kbps	IEEE 802.15.4 compliant
RF Power	-25dBm ~ 0dBm	Software Configurable
Range	~120m(outdoor), 20~30m(indoor)	Longer ranges possible with optional SMA antenna attached
Current Draw	RX: 18.8mA TX: 17.4mA Sleep mode: 1uA	Lower RF Power Modes reduce consumption
RF Power Supply	2.1V ~ 3.6V	CC2420 Input Power
Antenna	Dipole Antenna / PCB Antenna	Additional SMA connector available for extra antenna

Power consumption

XM1000: Power Supply

- XM1000 uses 2 AA batteries to supply 3V
- Current drawn simultaneously from both batteries

- Primary AA battery capacity
  - Zinc–carbon (dry cell): 400–900mAh
  - Zinc-chloride (heavy duty): 1000-1500mAh
  - Alkaline: 1700-3000mAh

- Rechargeable AA battery capacity
  - Nickel–cadmium (NiCd): 500–1100mAh
  - Nickel–metal hydride (NiMH): 1300–2700mAh

Mote Lifetime

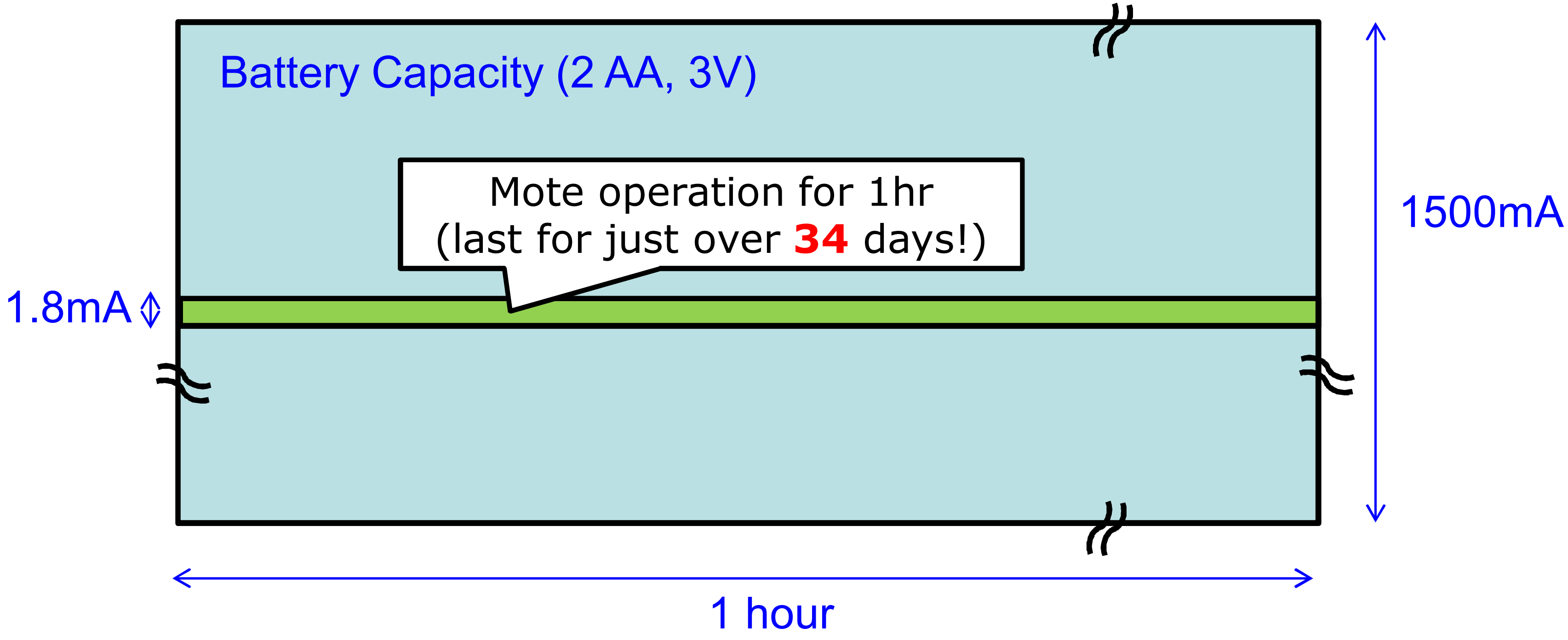
– Power Profile:

	MIN	NOM	MAX	UNIT
Supply voltage	2.1		3.6	V
Supply voltage during flash memory programming	2.7		3.6	V
Operating free air temperature	-40		85	°C
Current Consumption: MCU on, Radio RX		21.8	23	mA
Current Consumption: MCU on, Radio TX		19.5	21	mA
Current Consumption: MCU on, Radio off		1800	2400	μA
Current Consumption: MCU idle, Radio off		54.5	1200	μA
Current Consumption: MCU standby		5.1	21.0	μA

– For "MCU on, Radio off" mode:
  - Mote draws 1.8mA of current constantly
  - Thus average current drawn per hour = 1.8mA
  - Assume that the battery capacity is 1500mAh
  - Therefore the lifetime = 1500mAh/1.8mA = 833.3hrs or 34 days (rough estimation)

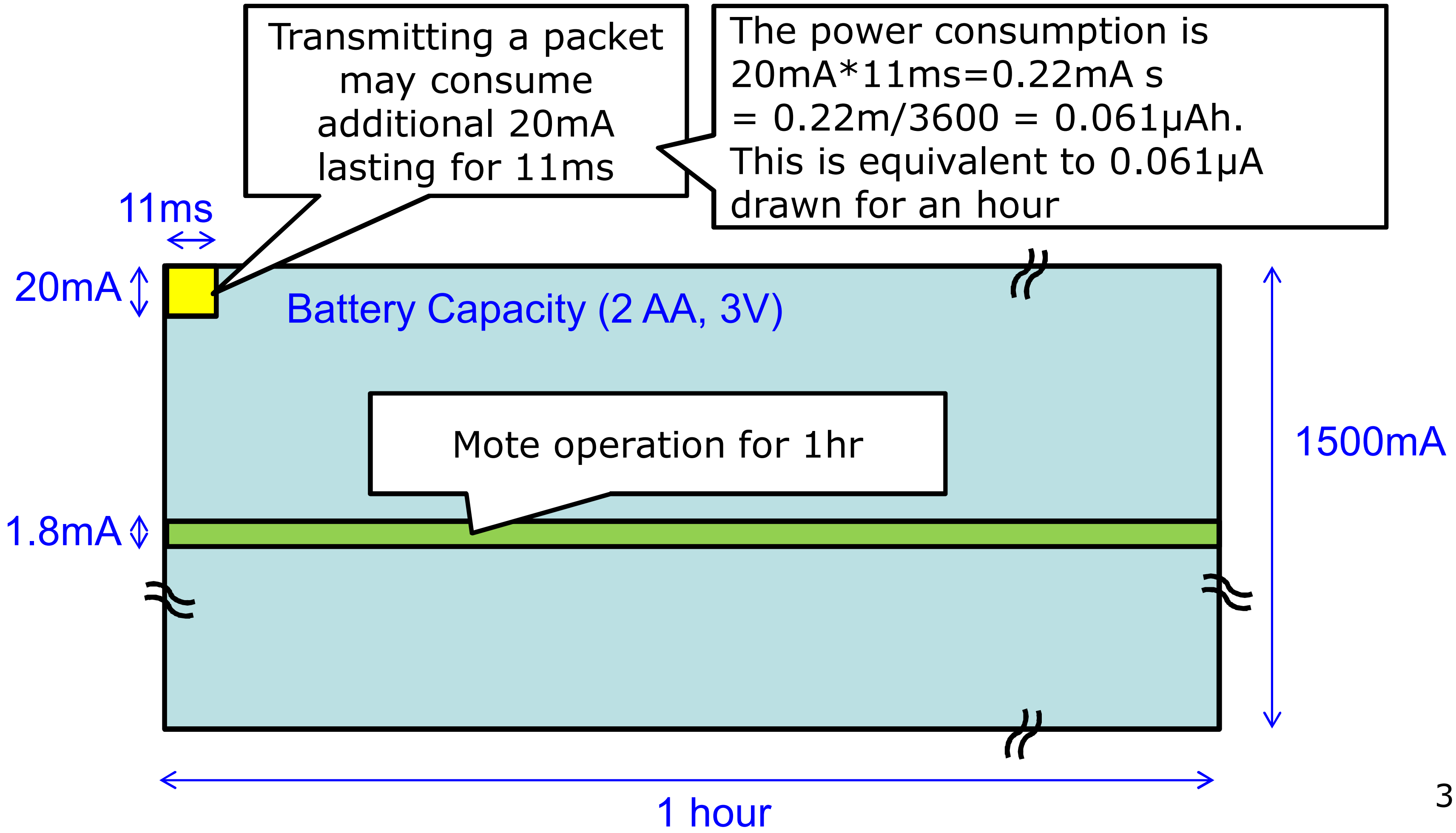
Power consumption map

– Battery capacity 1500mAh means the battery can continuously supply 1500mA for an hour



Power consumption map

– Additional activities on the mote means more current is drawn leading to shorter lifetime



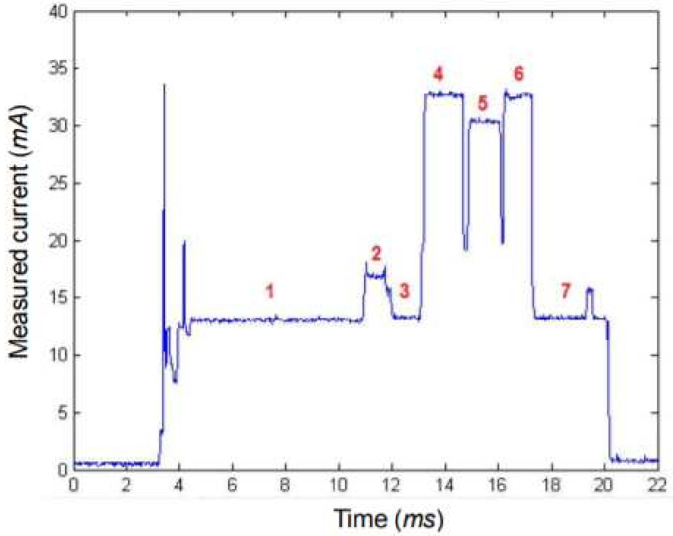
Power consumption (measured)

– Based on the work: Eduardo Casilari, Jose M. Cano-García and Gonzalo Campos-Garrido, "Based on Modeling of Current Consumption in 802.15.4/ZigBee Sensor Motes," Sensors 2010.

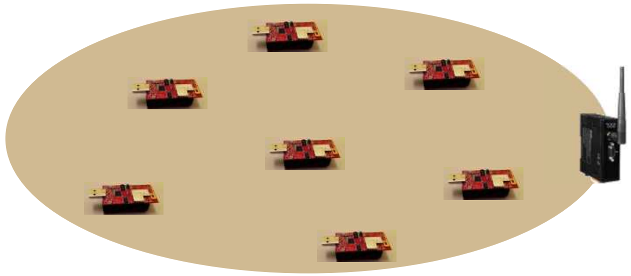
Table 1. Summary of drained current for different 802.15.4/ZigBee operations in the CC2480 mote.

Operation	State	Mean Required Current (mA)	Duration (ms)
Inactivity	Sleep mode	0.00075 mA	Variable
Start-up	Power-up of the microcontroller	2 mA	1,100 ms
	Waiting period (microcontroller and ZigBee processor are active)	15.5 mA	Variable
Association to the Coordinator	Scanning in 1 channel	26.6 mA	2,000
	Scanning in 16 channels	33.8 mA	up to 27,500
Transmission of a packet of *n* bytes with sensed data	Transmission of a *n*- byte packet	30.5 mA	$0.99 + (8 \times n)/250$
	Listening of the channel: CSMA wait, CCA, Reception of ACK	32.5 mA	2.9 ms
	Activation/deactivation of the ZigBee processor (radio transceiver is off)	13 mA	13 ms
Loss of connection (orphan scan followed by active scan without answer)	Scanning in 1 channel	9.3 mA	Variable
	Scanning in 16 channels	27.6 mA	Variable

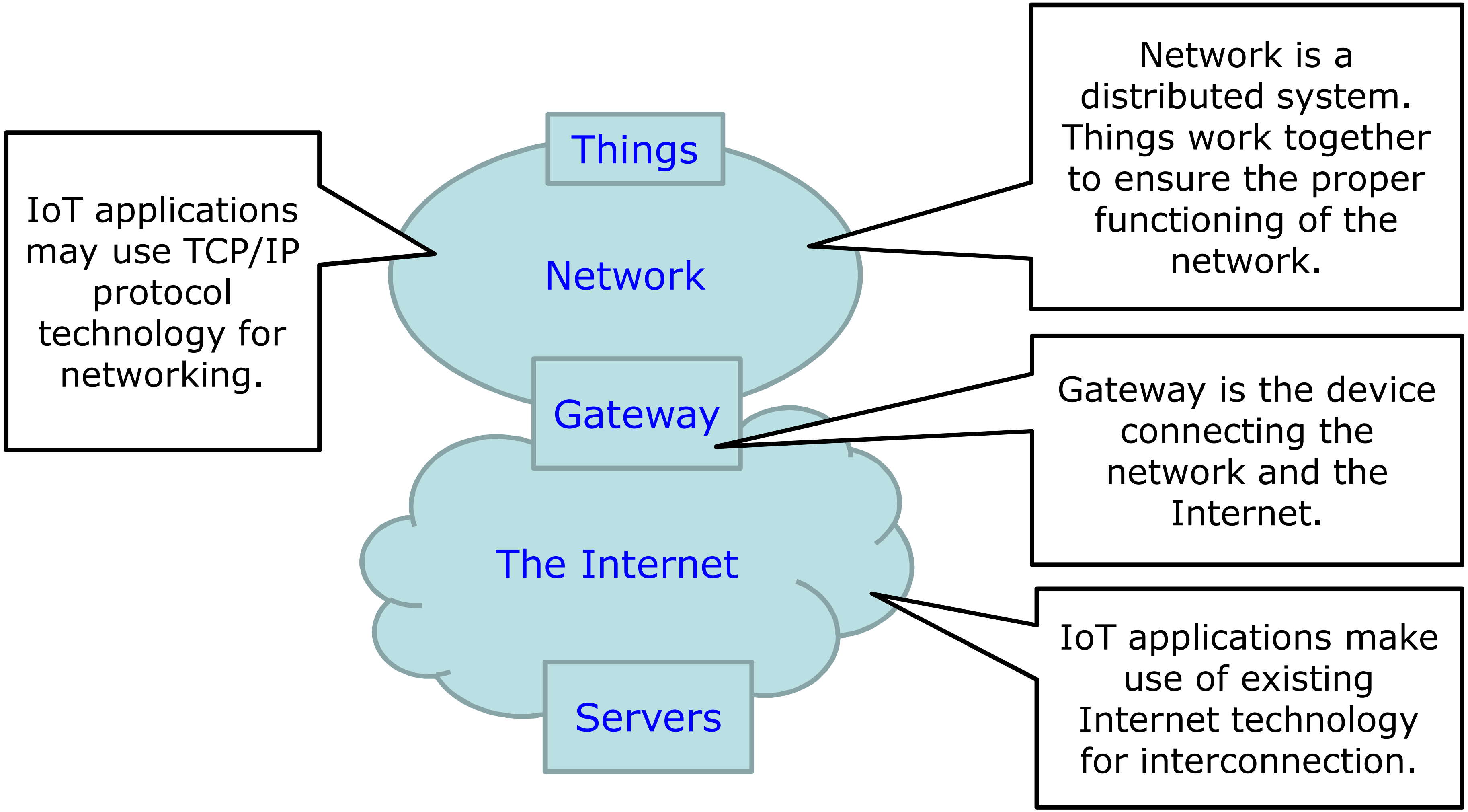
During the transmission of a data frame



Communication Architecture



IoT Networking



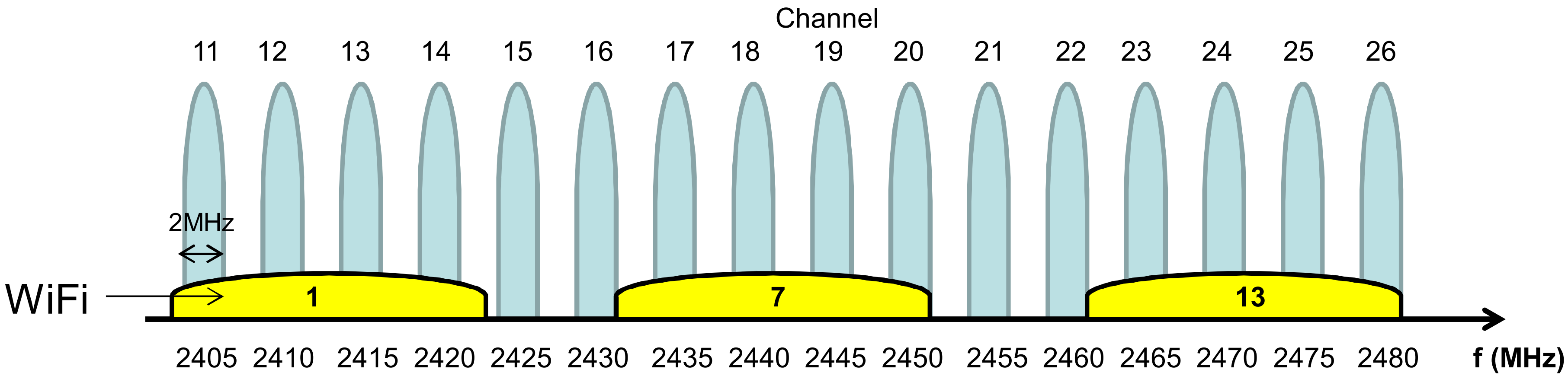
We focus on IEEE 802.15.4

IEEE 802.15.4 Standard

- IEEE 802.15.4 Standard specifies communication technologies for low-rate wireless personal area networks (LR-WPANs).
  - Including PHY & Medium Access Control (MAC)
- Three possible frequency bands (unlicensed):
  - 868.0-868.6 MHz, 902-928 MHz, 2.4-2.485 GHz
- Maximum data rate: 250 kb/s
  - Different modulation schemes are used in different frequency bands
- References:
  - IEEE Std. 802.15.4™, 2015
  - Marco Naeve, Eaton Corp., IEEE 802.15.4 MAC Overview, 2004

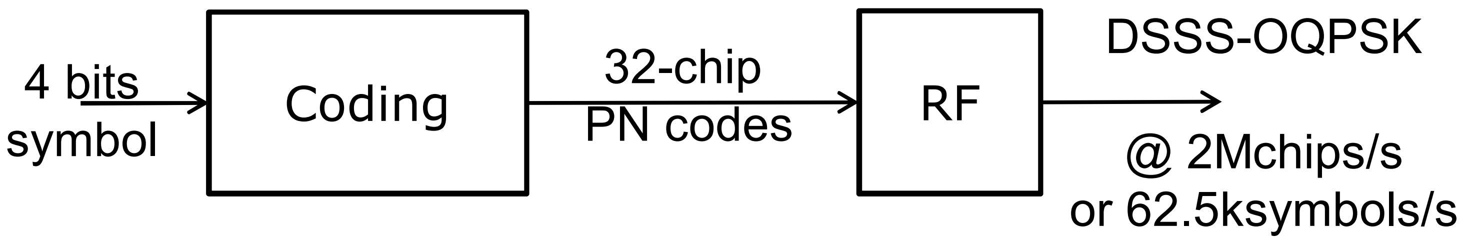
IEEE 802.15.4 at 2.4GHz

– IEEE 802.15.4 Frequency Band at 2.4GHz



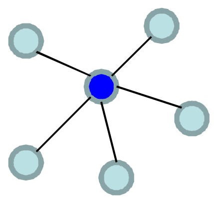
– PHY (2.4GHz)

 – 250 kbps (4 bits/symbol @ 62.5kBaud)

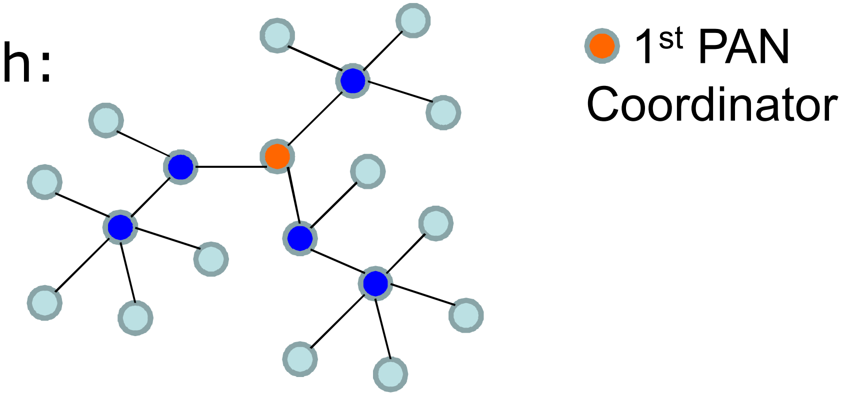


IEEE 802.15.4 MAC: Configuration

- Network topologies:
  - Star:



Mesh:



- Device classes:
  - Full Function Device (FFD): can act as a coordinator for a PAN ( ), communicate with any other device
  - Reduced Function Device (RFD): only communicate with coordinator
- Mesh (or Cluster Tree Network)
  - The first PAN coordinator instructs a device to become the PAN coordinator of a new cluster adjacent to the first one. Other device gradually connect and form a mesh.

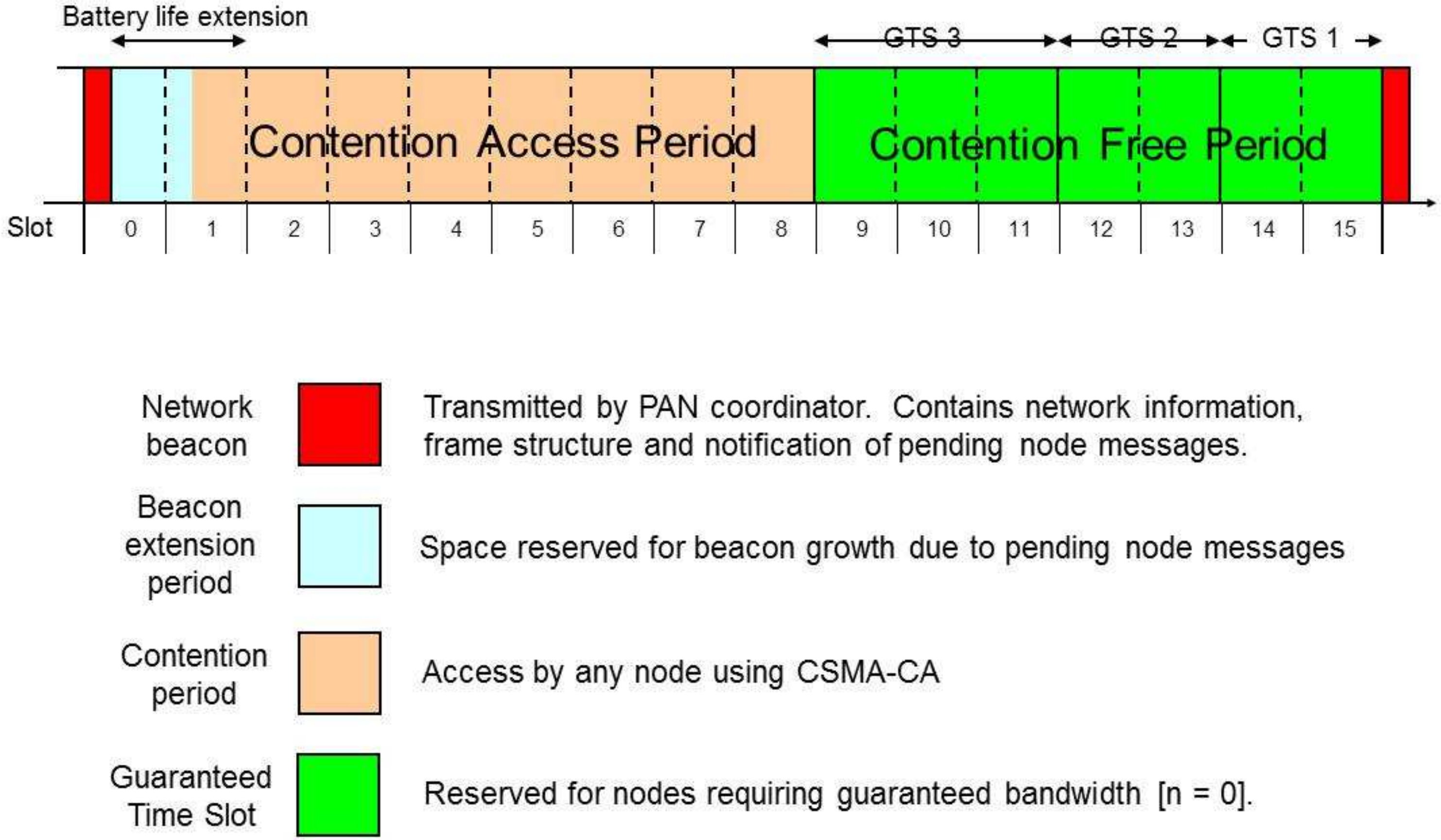
IEEE 802.15.4 MAC: Mode

- Beacon-mode
  - Make use of coordinator to coordinate transmission
  - Coordinator transmits a beacon to synchronize data transmission
  - All other nodes scan for the beacon and then use CSMA-CA to access the superframe on the channel
  - Transmission may be contention free using guaranteed time slots (GTS) assigned by coordinator

- Non-beacon mode
  - For point-to-point network
  - Nodes use unslotted CSMA-CA to access the channel
  - Less configuration, but receivers need to listen to the channel continuously

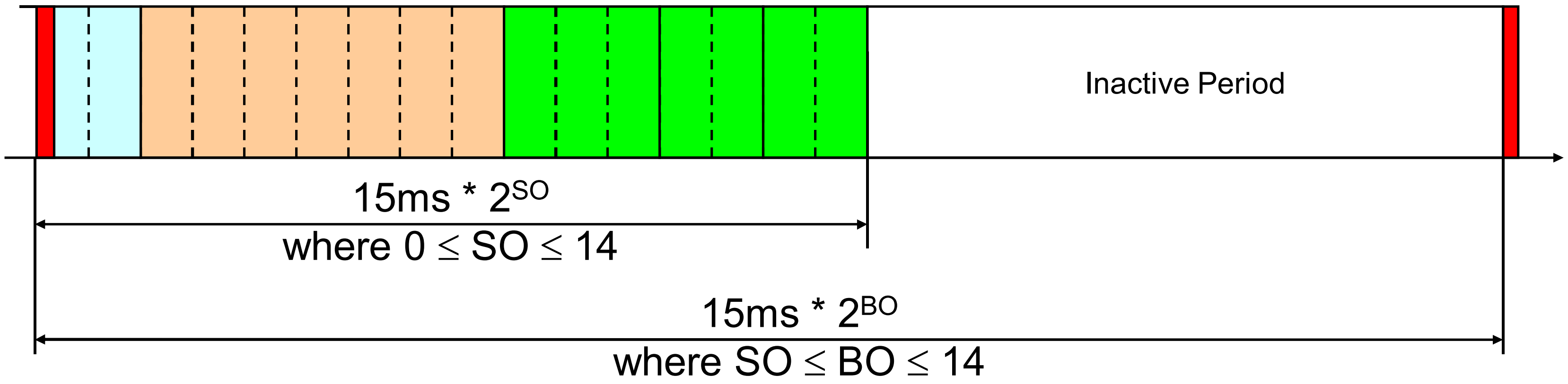
IEEE 802.15.4 MAC: Superframe

– Superframe (16 slots):



IEEE 802.15.4 MAC: Superframe

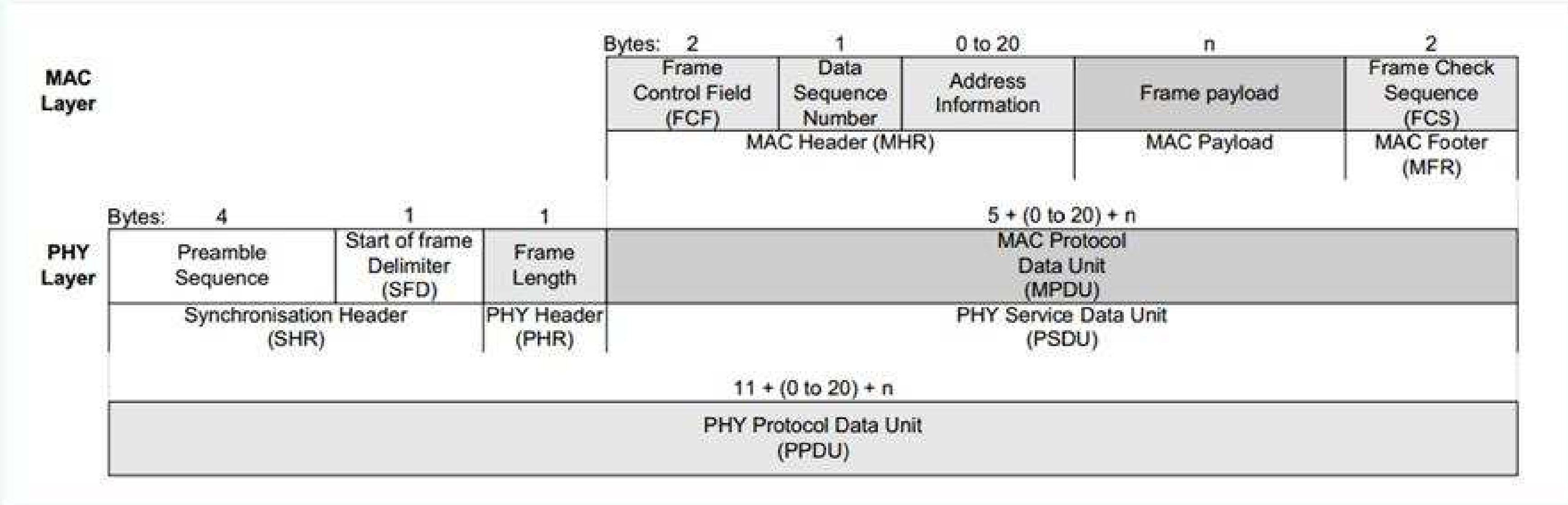
– Superframe Active/Inactive periods:



SO = Superframe order
BO = Beacon order

– All nodes can sleep during the inactive period

IEEE 802.15.4 MAC: Frame Format



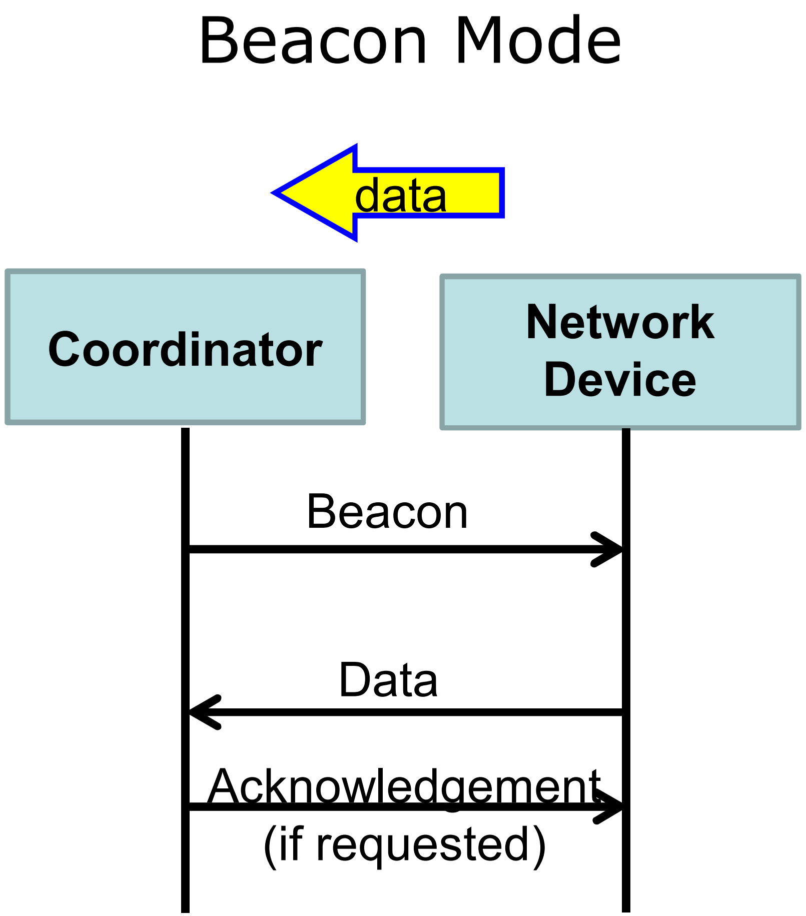
IEEE 802.15.4 Frame Format

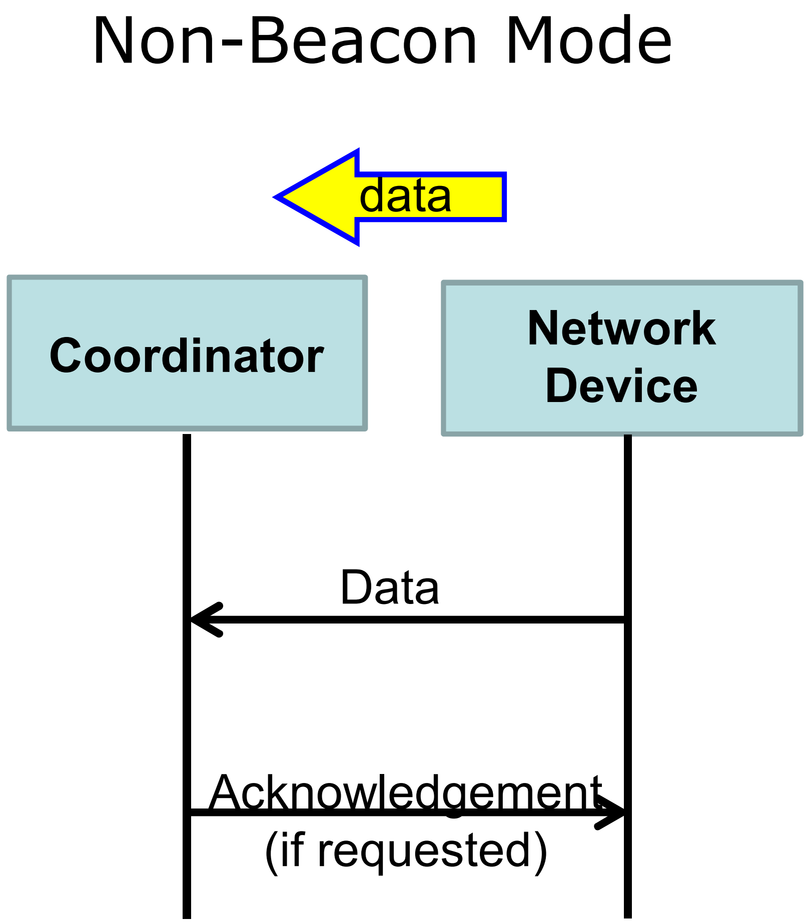
IEEE 802.15.4 MAC: Data Transfer

- Nodes use CSMA-CA to access the channel and transmit their data
  - Random delay is imposed to access an idle channel
  - In beacon-mode, all nodes are synchronized in time

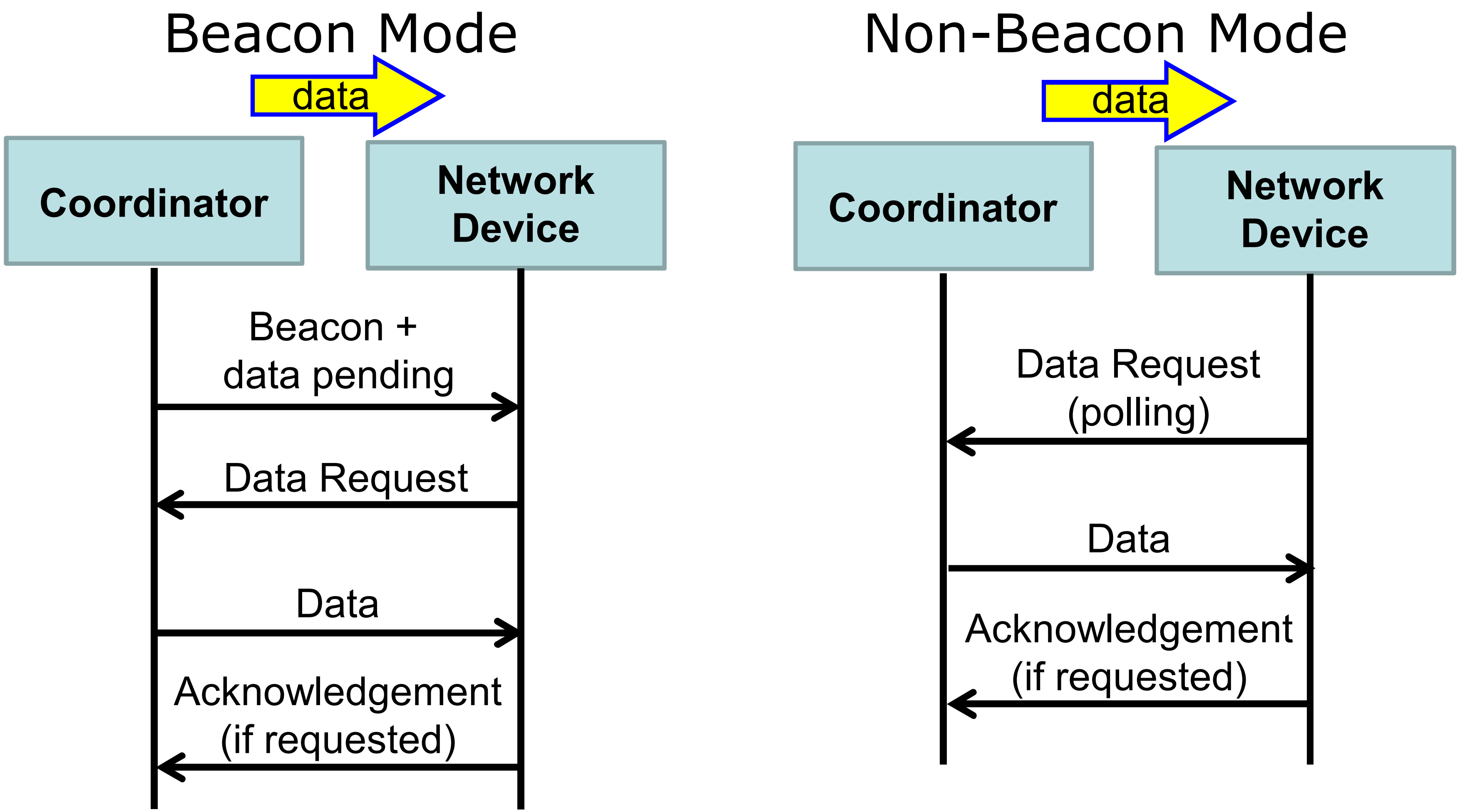
- A successful transmission may be acknowledged by the receivers
  - Acknowledgement frames are sent without CSMA-CA (that is, no random delay)
  - Timeout retransmission is used for acknowledged transmission
  - Transmission is always considered successful for unacknowledged transmission

IEEE 802.15.4 MAC: Data Transfer to a Coordinator





IEEE 802.15.4 MAC:
Data Transfer from a Coordinator



CSMA-CA Algorithm

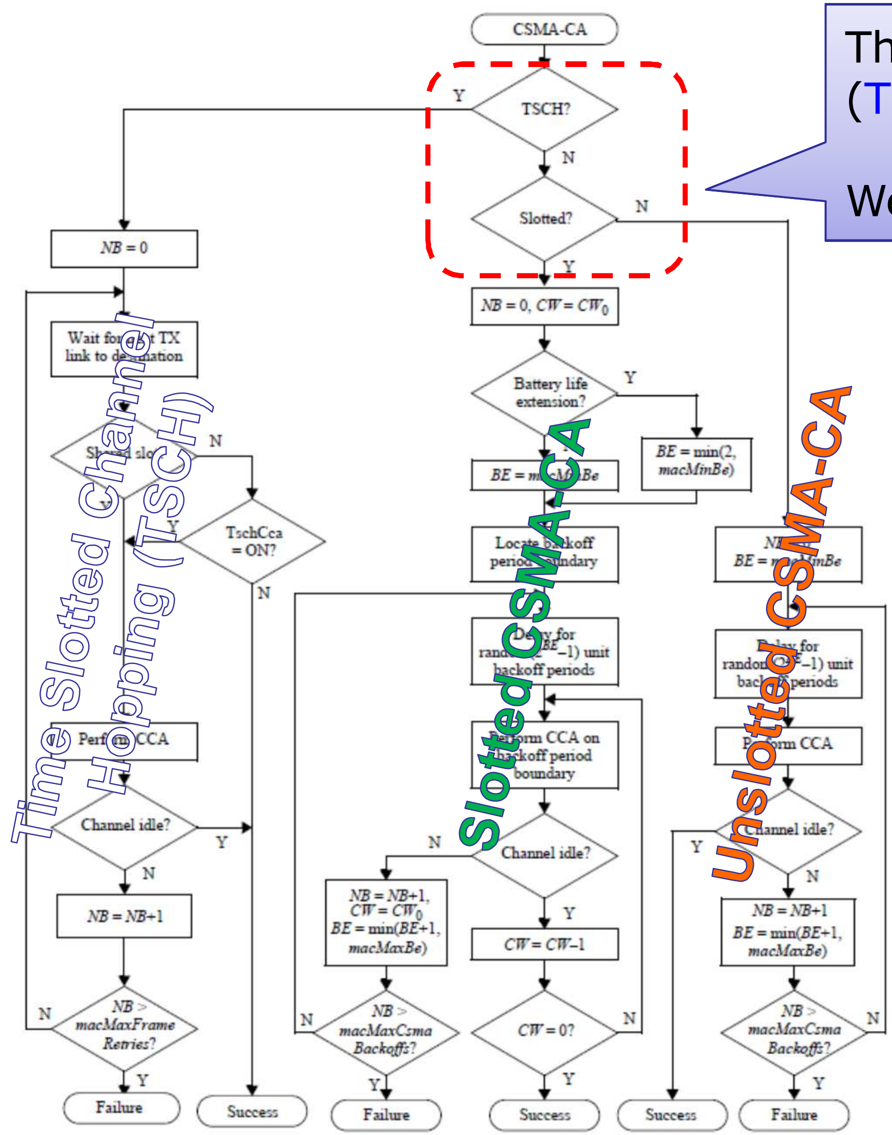
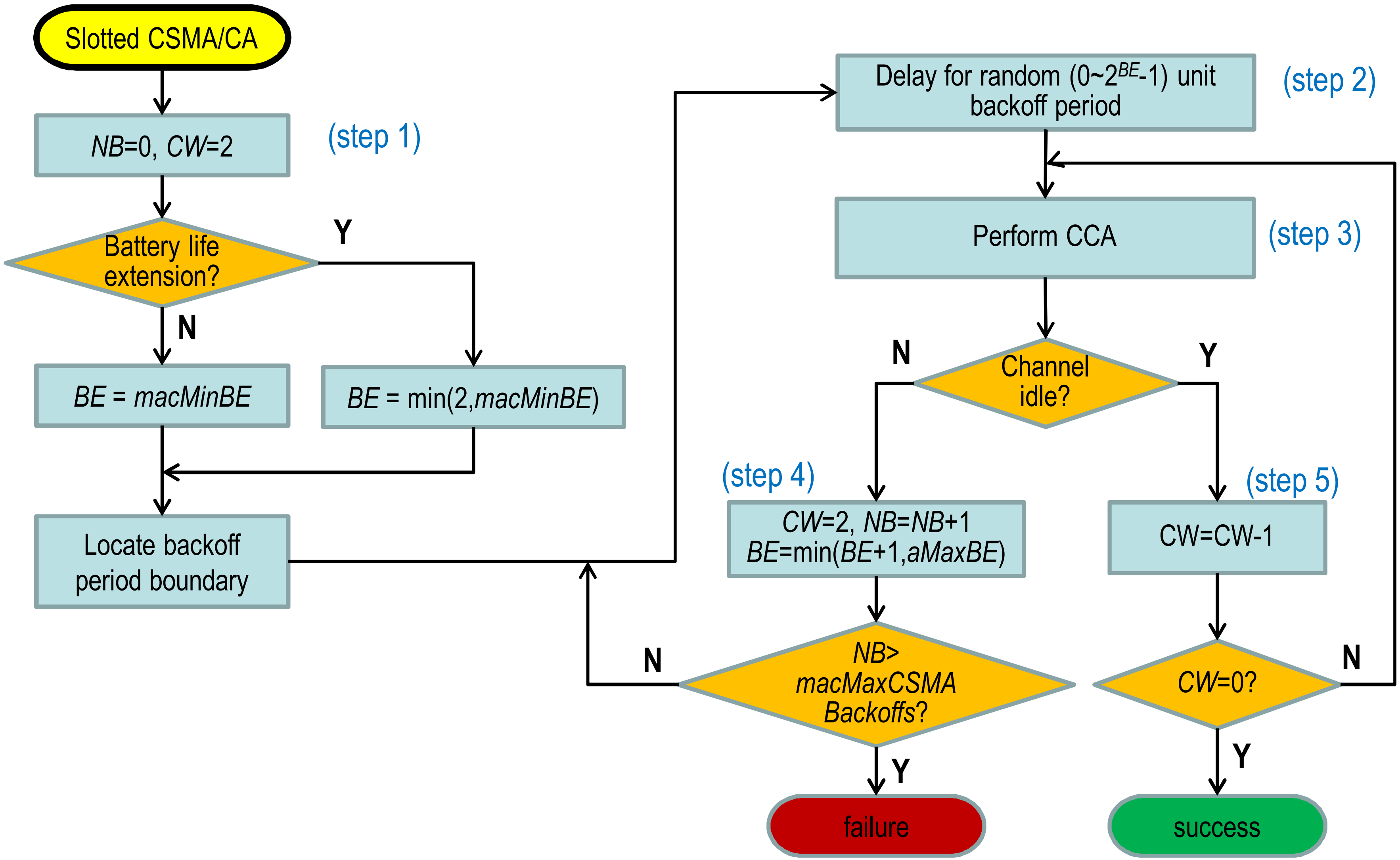


Figure 6-5—CSMA-CA algorithm

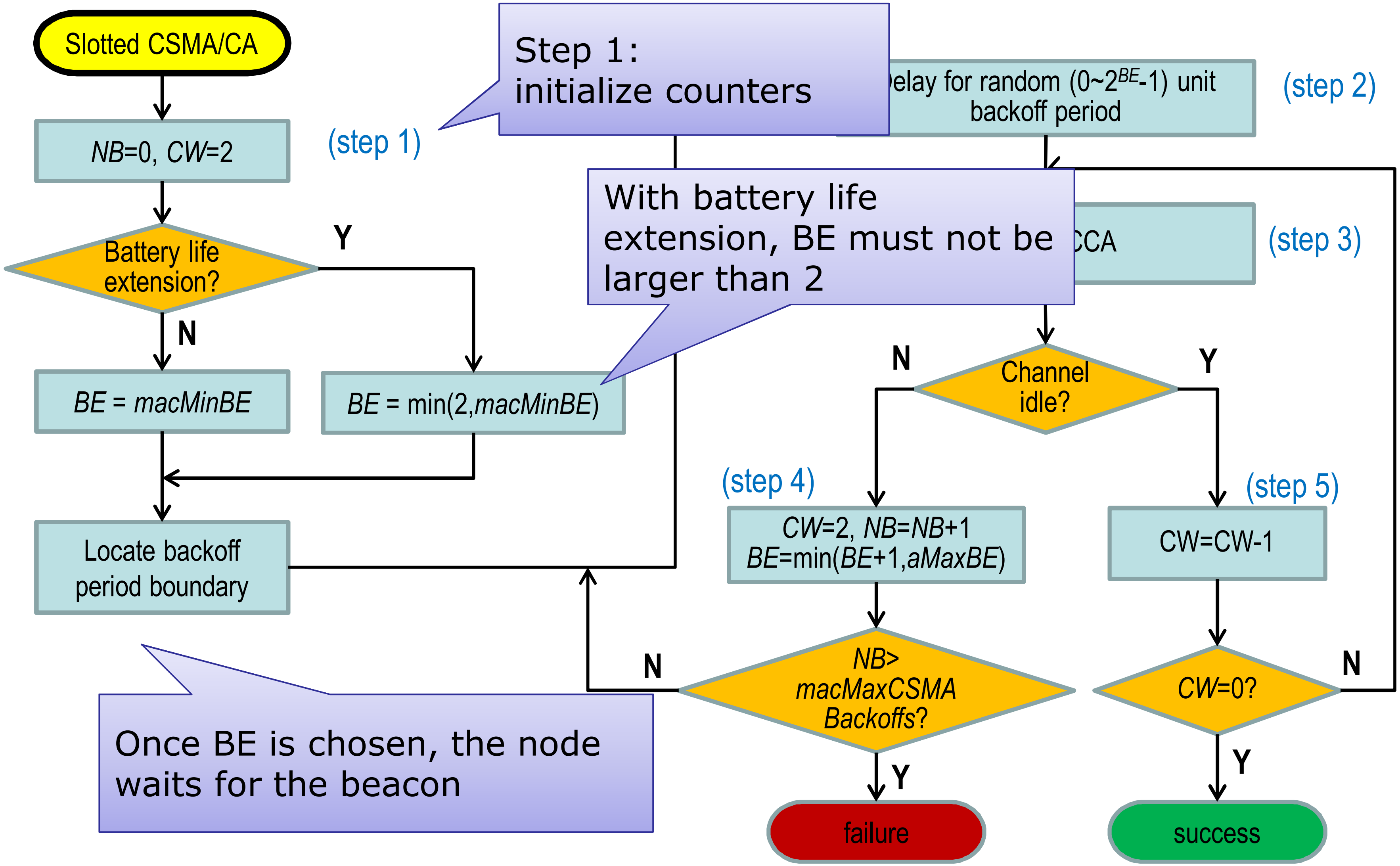
The standard mentioned three cases (TSCH, Slotted, Unslotted).

We focus on Slotted & Unslotted only.

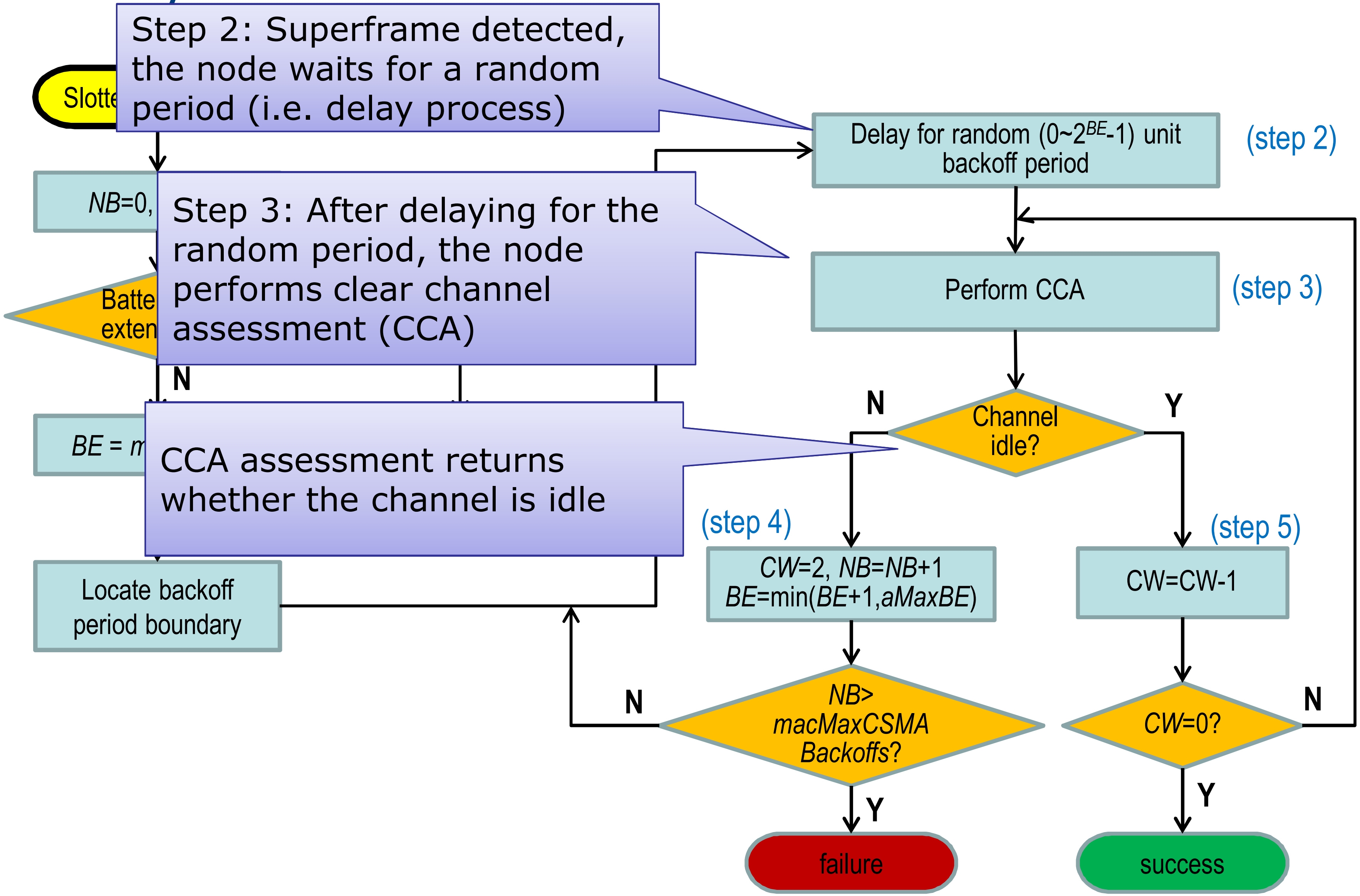
IEEE 802.15.4 MAC: CSMA/CA Channel Access



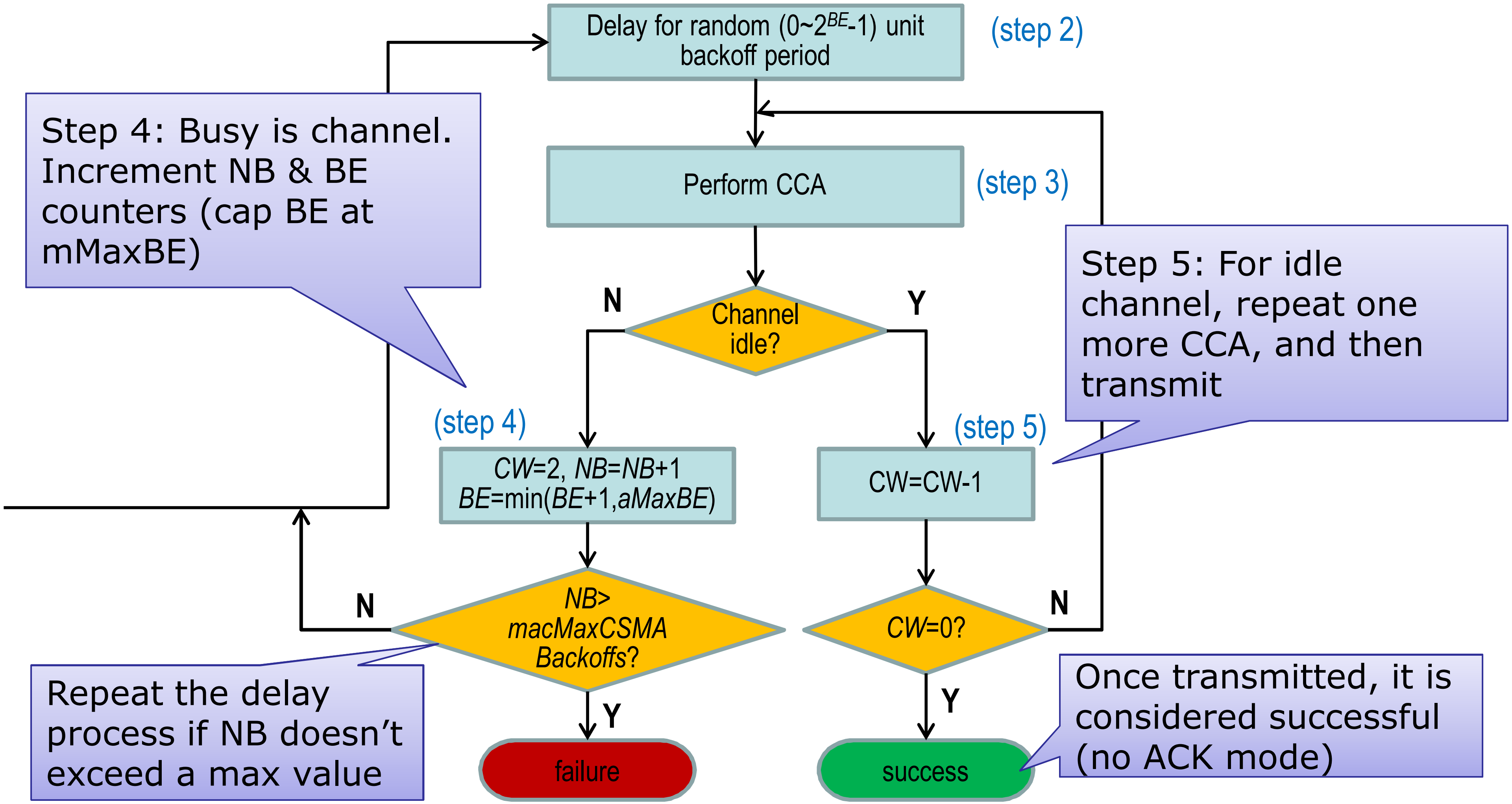
IEEE 802.15.4 MAC: CSMA/CA Channel Access



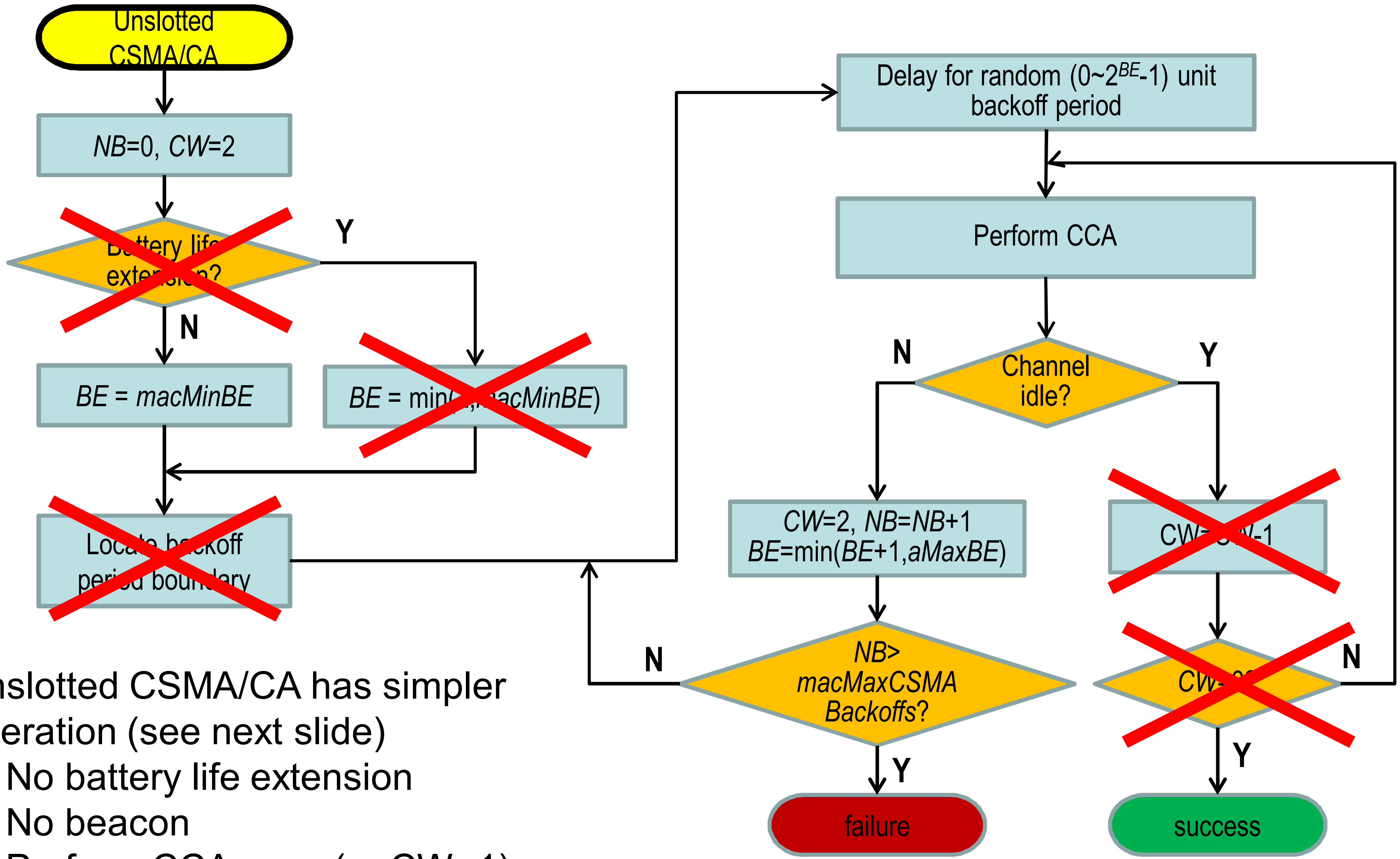
IEEE 802.15.4 MAC: CSMA/CA Channel Access



IEEE 802.15.4 MAC: CSMA/CA Channel Access



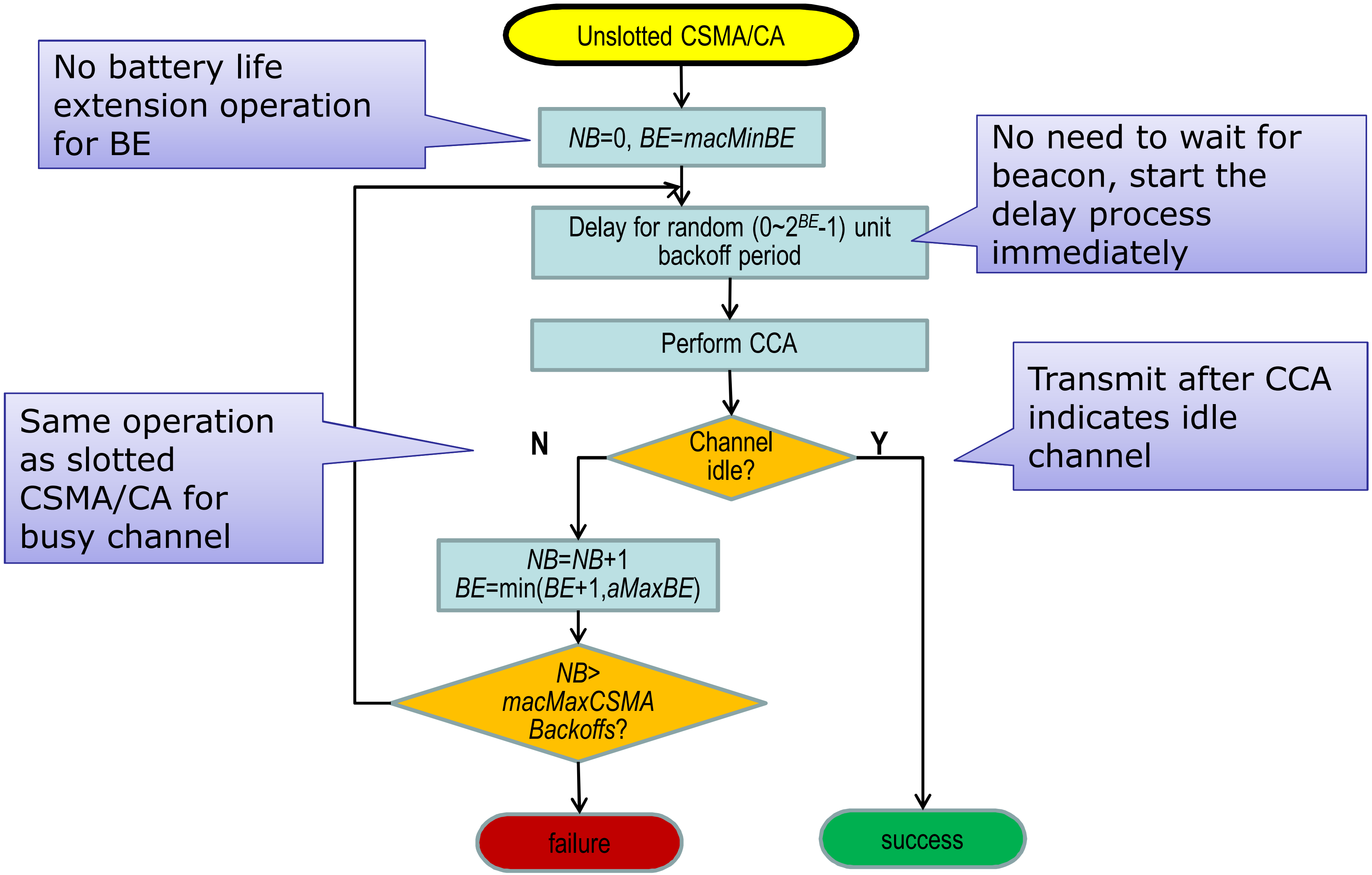
IEEE 802.15.4 MAC: Unslotted CSMA/CA Channel Access



Unslotted CSMA/CA has simpler operation (see next slide)

- No battery life extension
- No beacon
- Perform CCA once (or CW=1)

IEEE 802.15.4 MAC: Unslotted CSMA/CA Channel Access



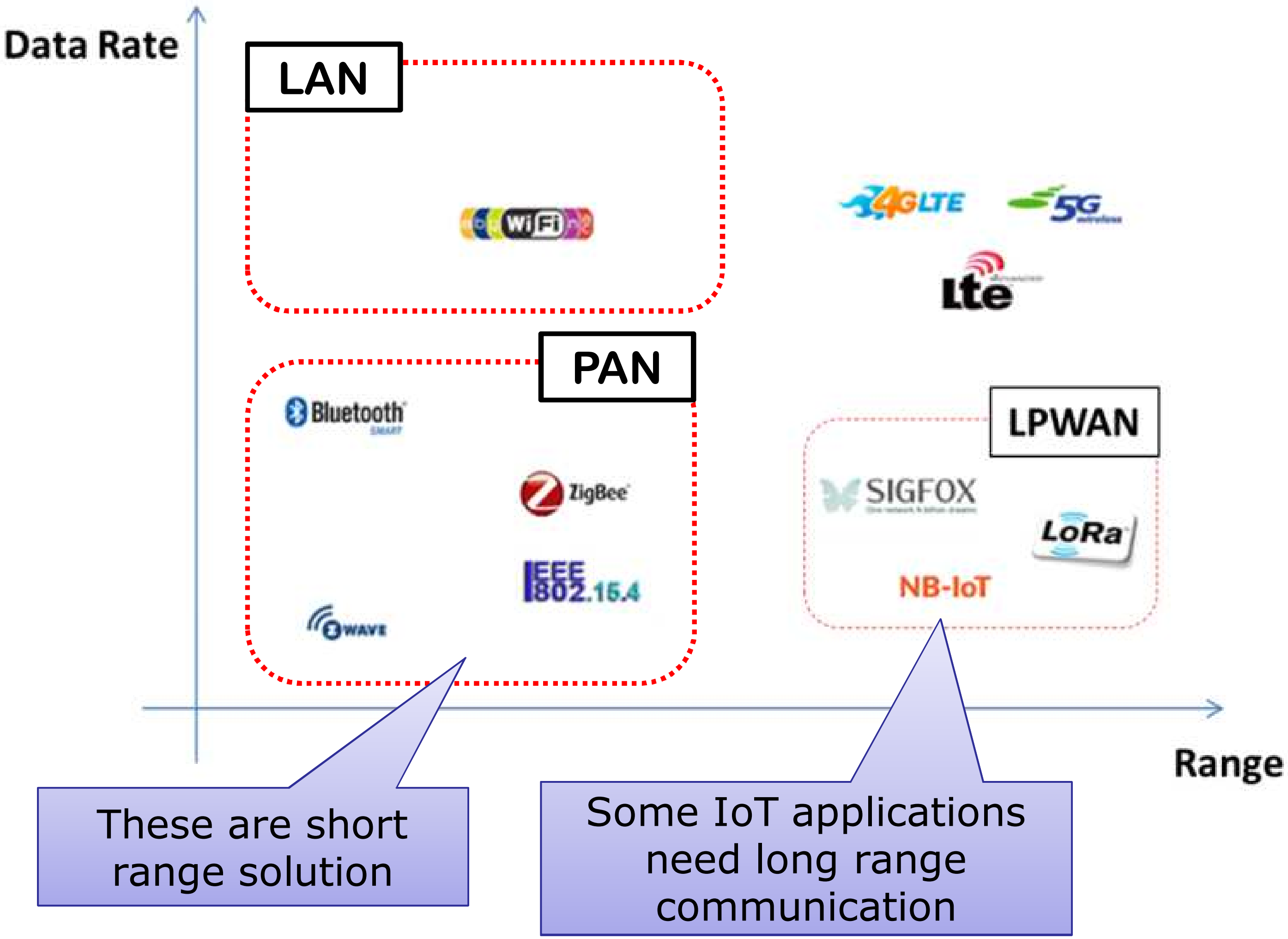
IEEE 802.15.4 MAC: Guaranteed Time Slot (GTS)

- GTS offers contention-free access within the superframe
- PAN coordinator is responsible for GTS allocation
  - up to seven GTSs at the same time
- GTS allocation is based on
  - GTS requests
  - The current available capacity in the superframe
- FFDs requiring fixed rates of transmissions can request for GTS
  - Need to track beacon to continue using GTS

Network Solution

Software implementation	Application Application Support Network	ZigBee, 6LoWPAN, etc (Making use of IEEE 802.15.4 features to build a networking solution)
Hardware implementation	IEEE 802.15.4 MAC IEEE 802.15.4 PHY	IEEE 802.15.4 (Solution for point-to-point communications)

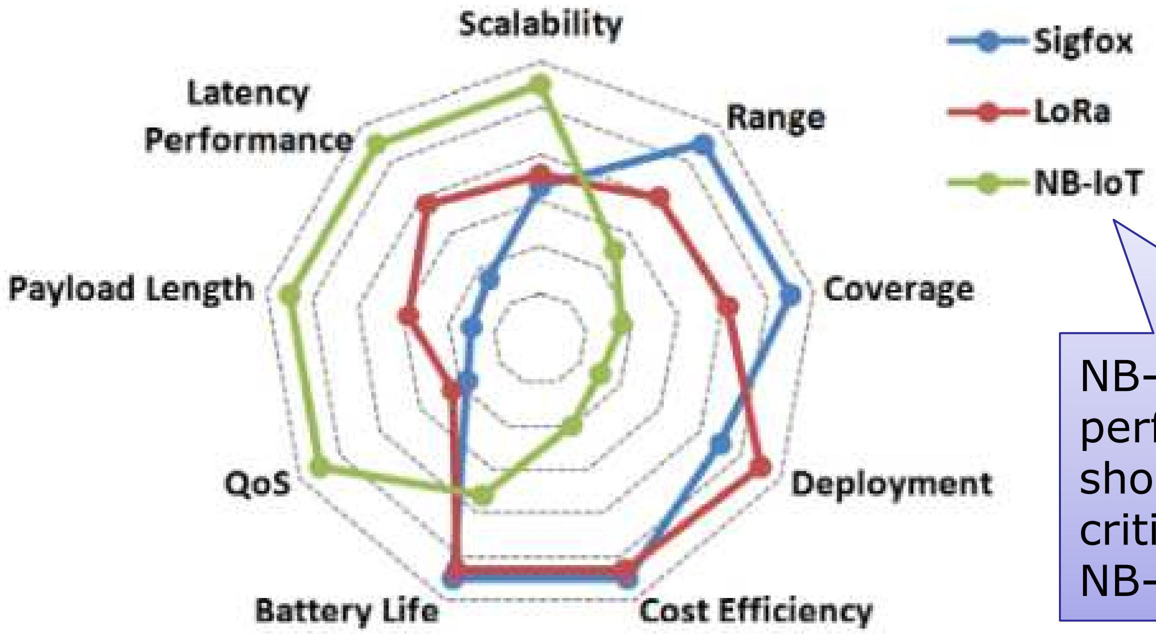
Solutions for Low Power Wide Area Networks (LPWANs)



Popular LPWAN solutions

- **SigFox** is a French global network operator founded in 2009 that builds wireless networks to connect low-power objects.
  - Proprietary technology. Network is operated through SigFox, need subscription.
- **LoRa** (Long Range) is a LPWAN technology.
  - Open technology. Any user can deploy a gateway to run a network.
- **Narrowband-IoT** (NB-IoT) is a LPWAN radio technology standard developed by 3GPP (cellular network standardization group). 3GPP also has another standard for machine type communications called **LTE-M**.
  - Open technology. Network is operated through a Telco on a licensed band. Expensive to deploy.

Comparison



NB-IoT has better performance, but falls short on many features critical to IoT
NB-IoT targets IIoT

Fig. 4. Respective advantages of Sigfox, LoRa, and NB-IoT in terms of IoT factors.

Source:
Kais Mekki, Eddy Bajic, Frederic Chaxel, Fernand Meyer, "Overview of Cellular LPWAN Technologies for IoT Deployment: Sigfox, LoRaWAN, and NB-IoT," IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), March 2018.

Comparison

Table 1. Overview of LPWAN technologies: Sigfox, LoRaWAN, and NB-IoT

	Sigfox	LoRaWAN	NB-IoT
Modulation	BPSK	CSS	QPSK
Frequency	Unlicensed ISM bands (868MHz in Europe, 915MHz in North America, and 433MHz in Asia)	Unlicensed ISM bands (868MHz in Europe, 915MHz in North America, and 433MHz in Asia)	Licensed LTE frequency bands
Bandwidth	100 Hz	250 kHz and 125 kHz	200 kHz
Maximum data rate	100 bps	50 kbps	200 kbps
Bidirectional	Limited / Half-duplex	Yes / Half-duplex	Yes / Half-duplex
Maximum messages/day	140 (UL), 4 (DL)	Unlimited	Unlimited
Maximum payload length	12 bytes (UL), 8 bytes (DL)	243 bytes	1600 bytes
Range	10 km (urban), 40 km (rural)	5 km (urban), 20 km (rural)	1 km (urban), 10 km (rural)
Interference immunity	Very high	Very high	Low
Authentication & encryption	Not supported	Yes (AES 128b)	Yes (LTE encryption)
Adaptive data rate	No	Yes	No
Handover	End-devices do not join a single base station	End-devices do not join a single base station	End-devices join a single base station
Localization	Yes (RSSI)	Yes (TDOA)	No (under specification)
Allow private network	No	Yes	No
Standardization	Sigfox company is collaborating with ETSI on the standardization of Sigfox-based network	LoRa-Alliance	3GPP

Source:

Kais Mekki, Eddy Bajic, Frederic Chaxel, Fernand Meyer, "Overview of Cellular LPWAN Technologies for IoT Deployment: Sigfox, LoRaWAN, and NB-IoT," IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops), March 2018.

Current LPWAN technologies

UNIVERSITY OF SURREY

IOT ANALYTICS

Insights that empower you to understand IoT markets

High-level overview of current LPWAN technologies

LPWAN technologies		Adjacent / comparative technologies
Licensed spectrum	**Unlicensed spectrum**	**Unlicensed spectrum**
Low-power technologies that operate in the licensed spectrum	Low-power technologies that operate in the unlicensed spectrum	Technologies that are not classified as LPWAN but have similar features and/or target similar use cases. They all use the unlicensed spectrum.
NB-IoT LTE-M EC-GSM-IoT THINGSTREAM	sigfox LoRa RPMA WEIGHTLESS nwave Telensa NB-Fi СТРИЖ helium SAT4M2M MIOTY hiber	Wi SUN WIREPAS Silver Spring Networks WiFi HaLow JupiterMesh DASH7

Source: IoT Analytics LPWAN Market Report 2018 - 2023

Check that you know…

- Understand the concept of a transfer function and apply it
- Derive transfer function based on some experimental information or data sheet specification
- Describe briefly sensor technologies
- Describe briefly the physical layer setup of IEEE 802.15.4
- Explain the network setup and MAC operation of IEEE 802.15.4
- Understand the differences between PAN and LPWAN, and be aware of some popular LPWAN technologies
- Compute the power consumption of a radio activity, and estimate the lifetime of a mote

Questions?