Lecture 4: Hardware Platform

Course code: COMP 413 - Internet of Things

Dr. Abdulkadir Köse
Computer Engineering Department
Abdullah Gül University

Email: abdulkadir.kose@agu.edu.tr

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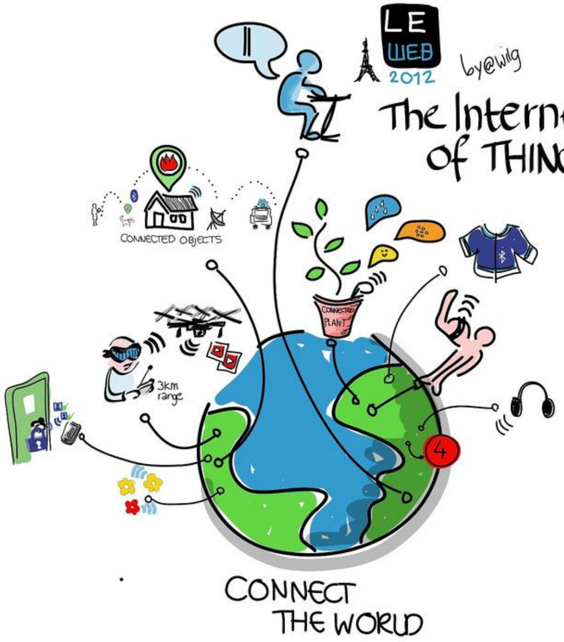


Overview

- 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.

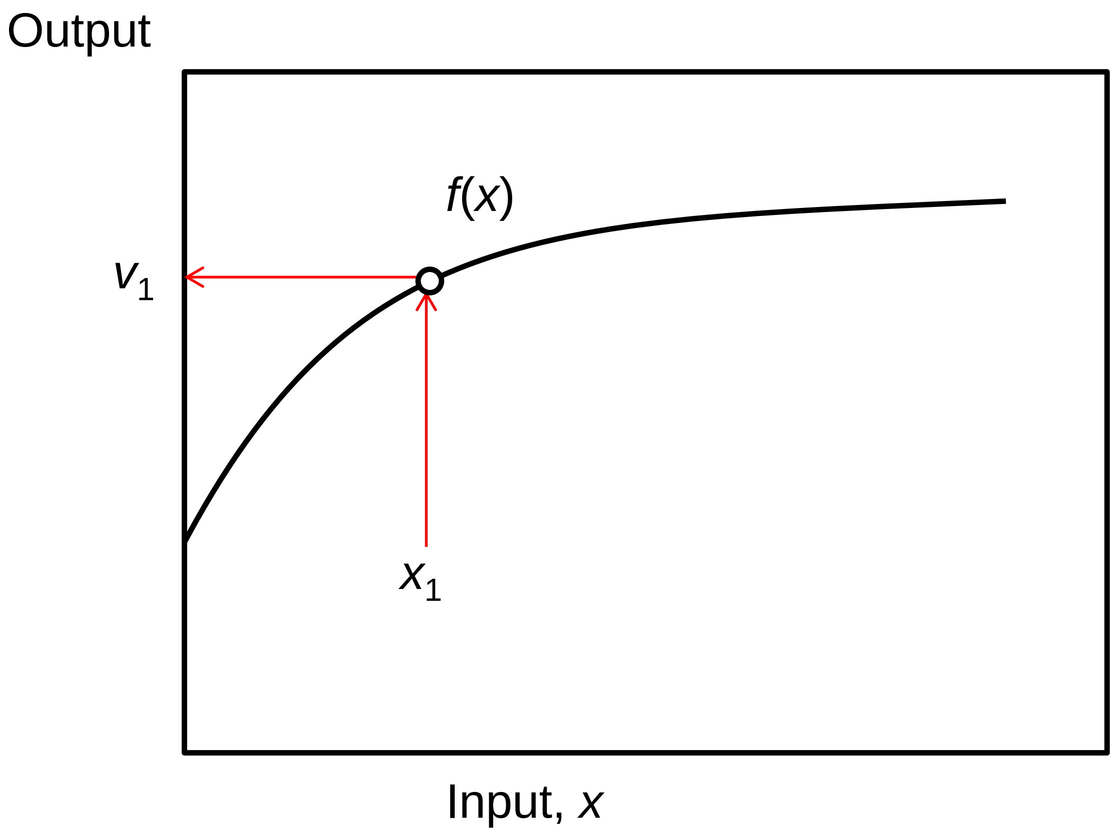
- The simplest form of transfer function is a linear function which can be described as follows.

$$S = a + bx$$

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:



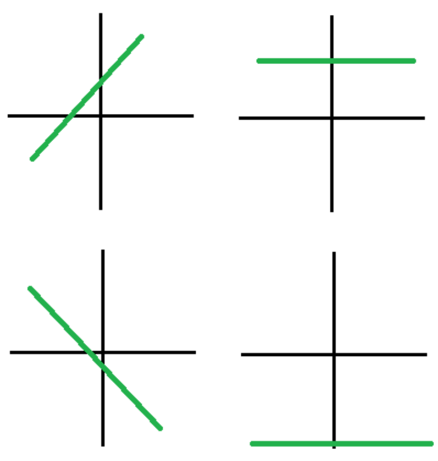
– Inverse transfer function: to tell the physical measured parameter based on sensor output.

Transfer Function: Linear/Nonlinear

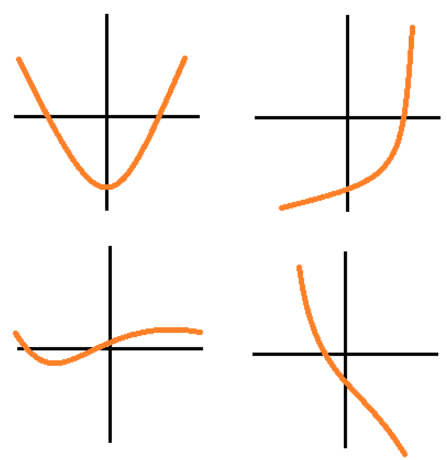
- Linear:
  - It can be described by a straight line:

$$S = a + bx$$

  - 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)



Linear Functions

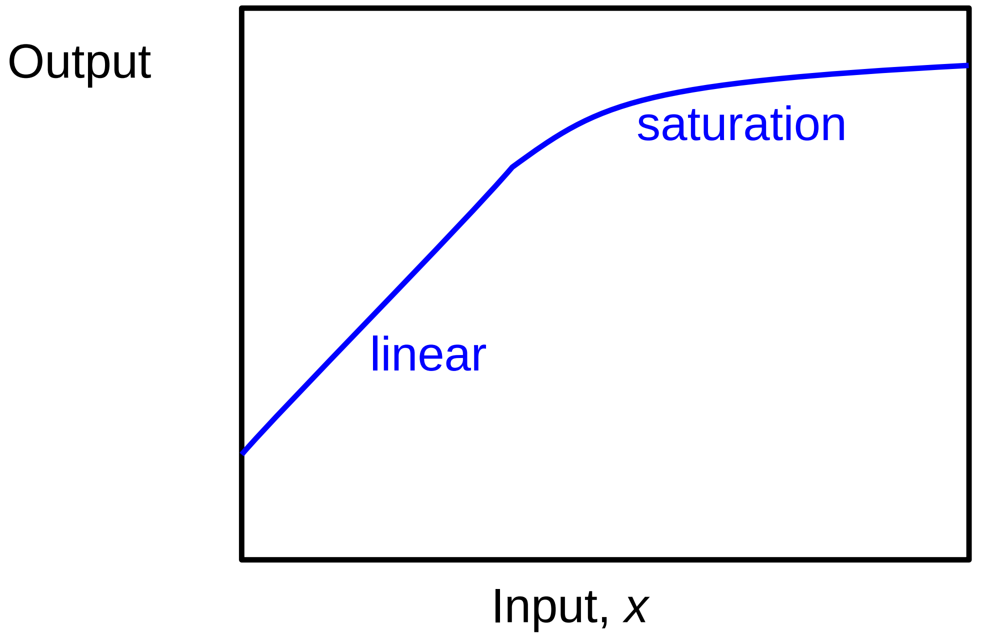


Nonlinear Functions

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

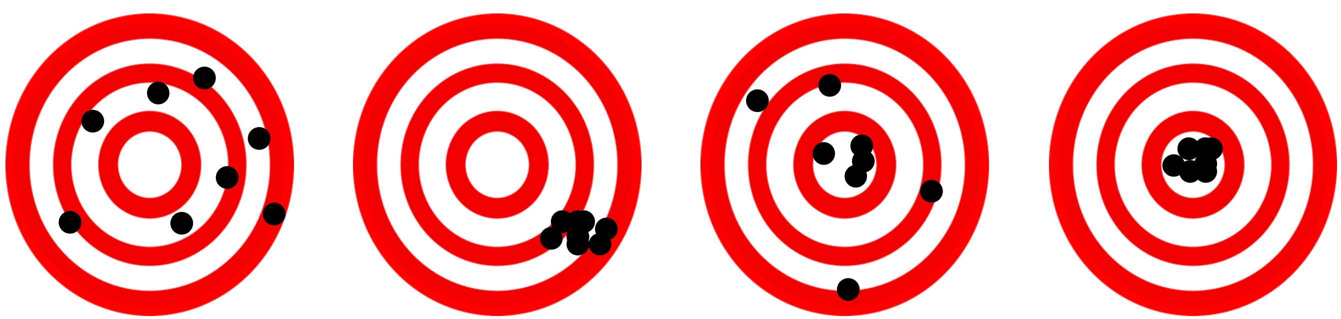


Transfer Function

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

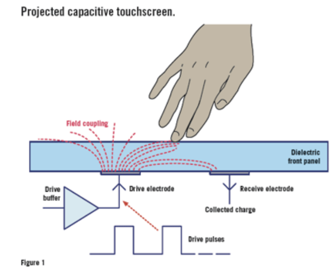
- Accuracy
  - It describes how close the measurement is to the true value

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

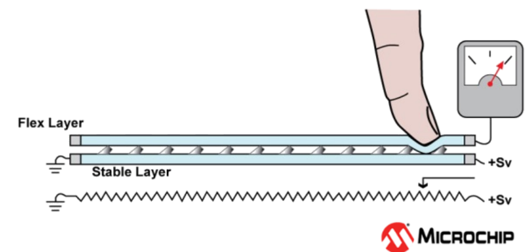


Accuracy:	Low	Low	High	High
Repeatability:	Low	High	Low	High

Sensors Technology
A Quick Overview



- 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

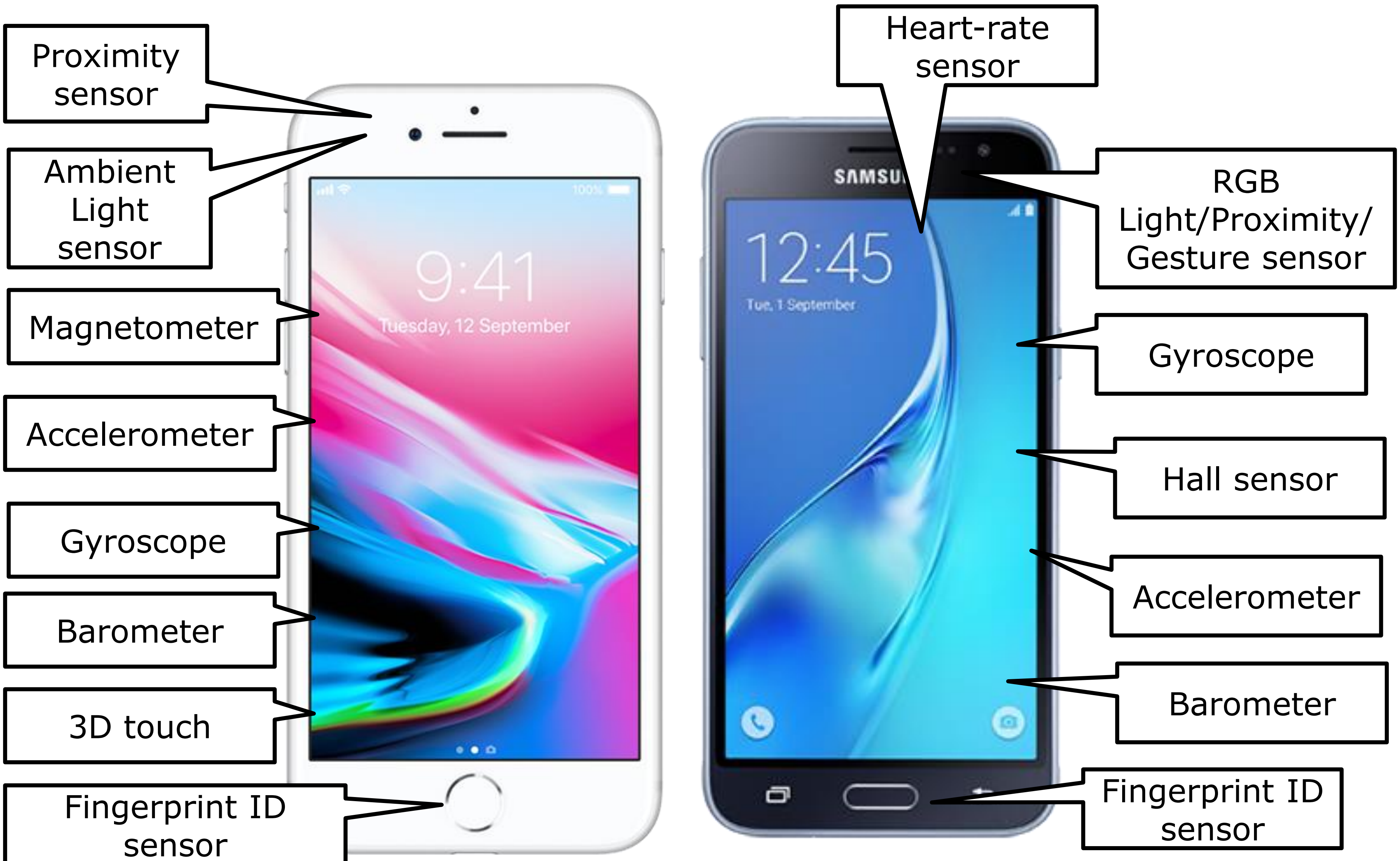
Sensors Technology
A Quick Overview

- 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

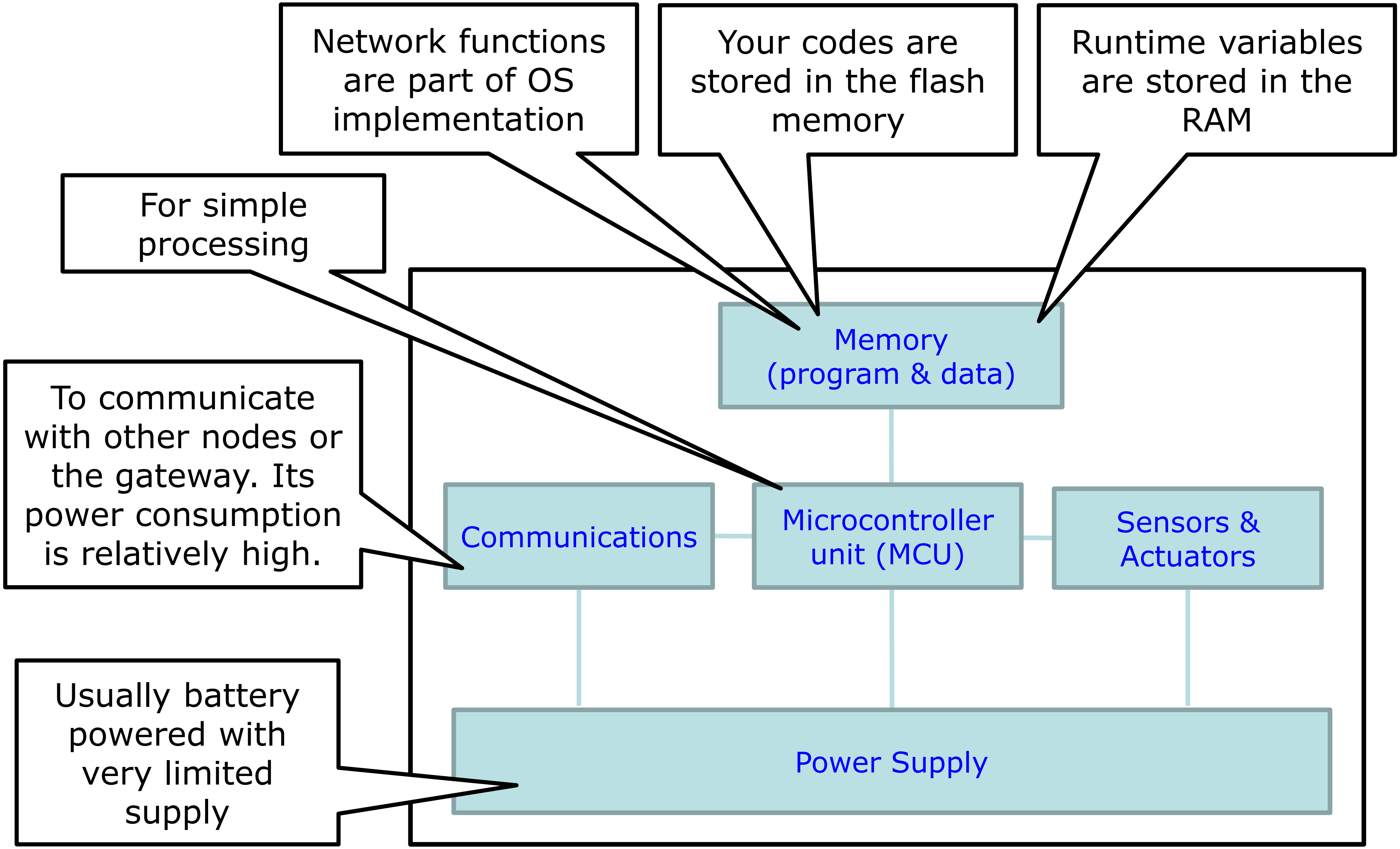


Actuators

- 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)

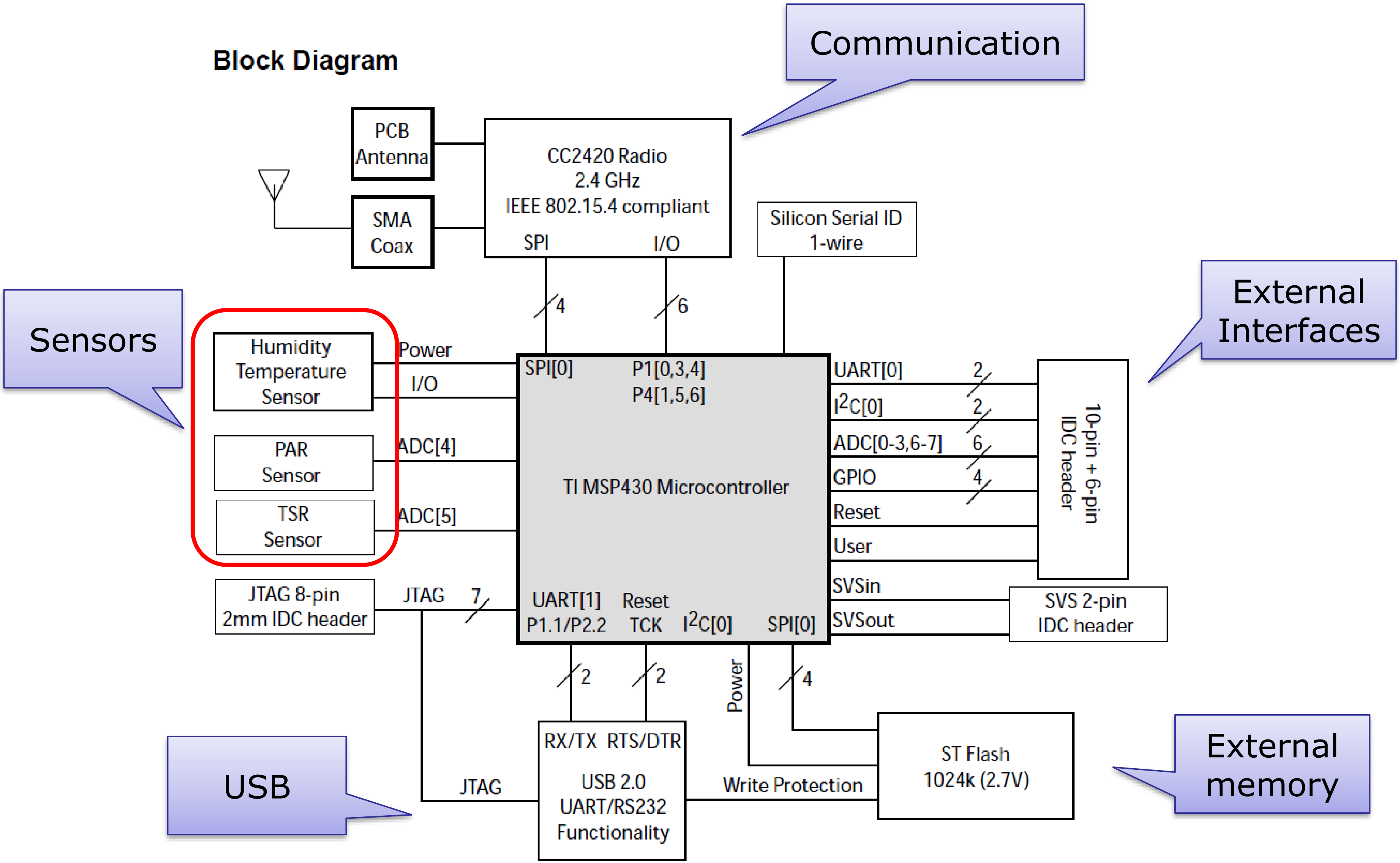
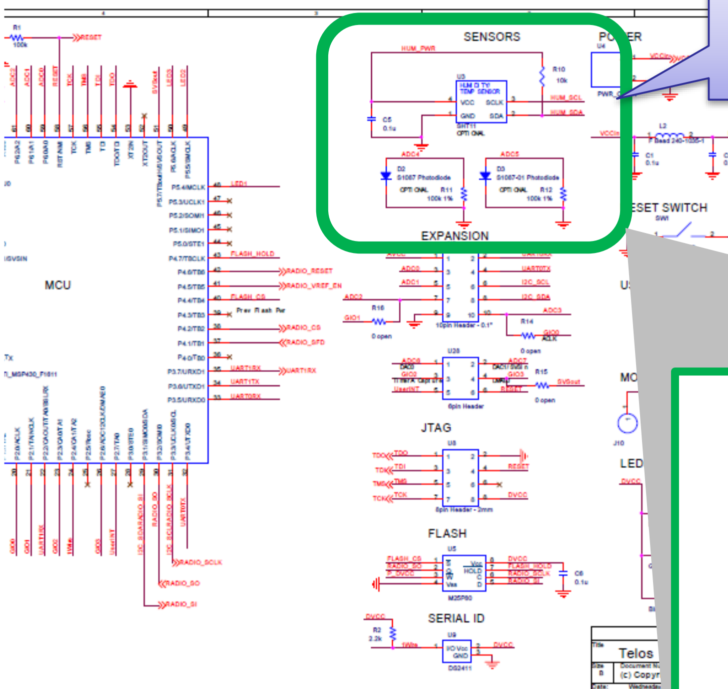


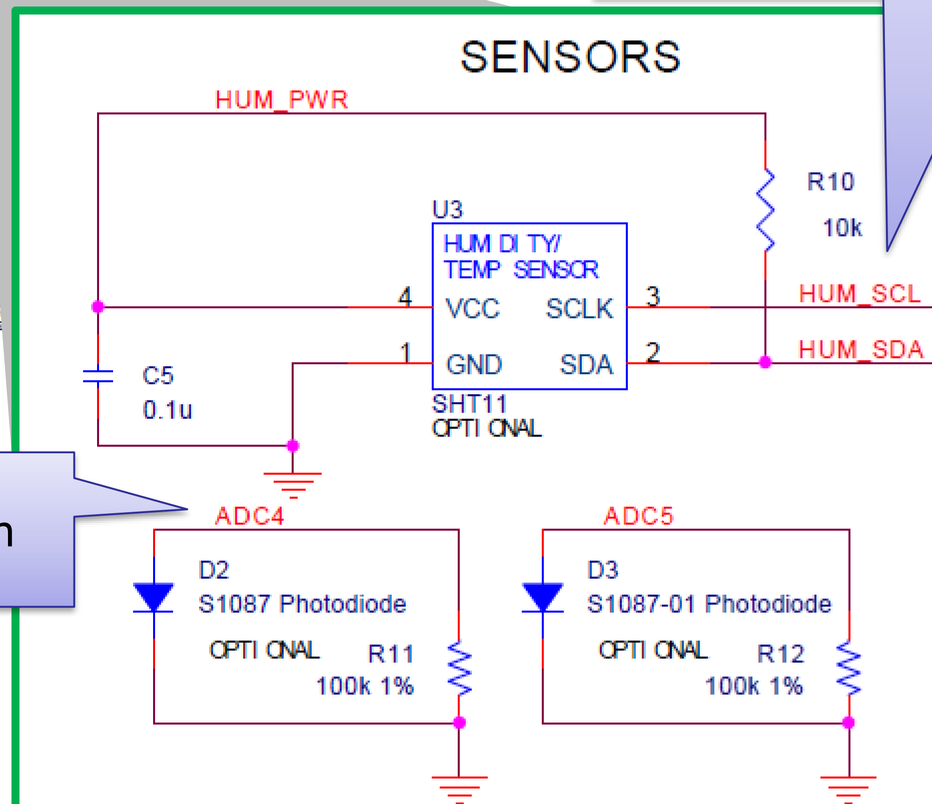
Figure 3 : Functional Block Diagram of the Telos Module, its components, and buses

Schematic (from the datasheet)



Sensors

Temp & Humidity sensors interface with MCU via I2C



Light sensors interfaces with MCU via ADC

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

XM1000: Sensors

Sensor Performance

Relative Humidity

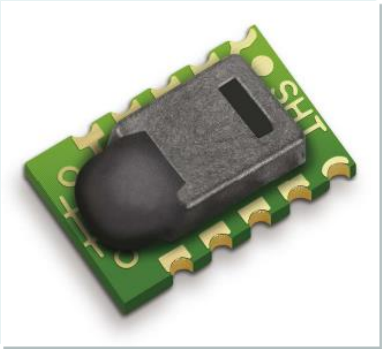
Parameter	Condition	min	typ	max	Units
Resolution [1]		0.4	0.05	0.05	%RH
		8	12	12	bit
Accuracy [2] SHT10	typical		±4.5		%RH
	maximal	see Figure 2			
Accuracy [2] SHT11	typical		±3.0		%RH
	maximal	see Figure 2			
Accuracy [2] SHT15	typical		±2.0		%RH
	maximal	see Figure 2			
Repeatability			±0.1		%RH
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)

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

The sensor uses 14 bits

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

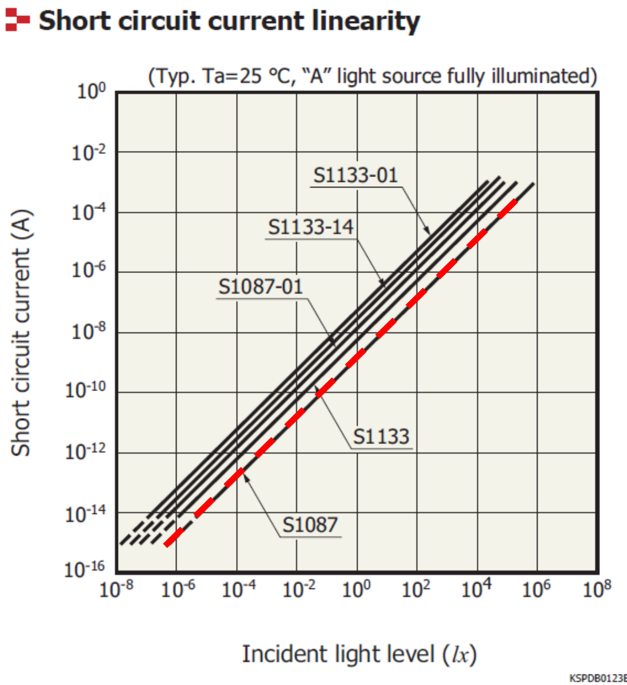
SO_T	d_2 (°C)	d_2 (°F)
14bit	$\boxed{0.01}$	0.018
12bit	0.04	0.072

We use 3V

Table 8: Temperature conversion coefficients[15].

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

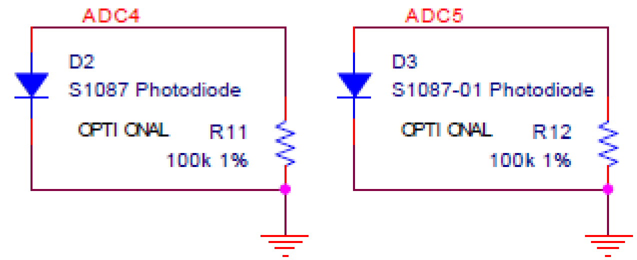
Light Sensor – S1087
(see ./platform/xm1000/apps/sensors/sensorReading.c under contiki folder)



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

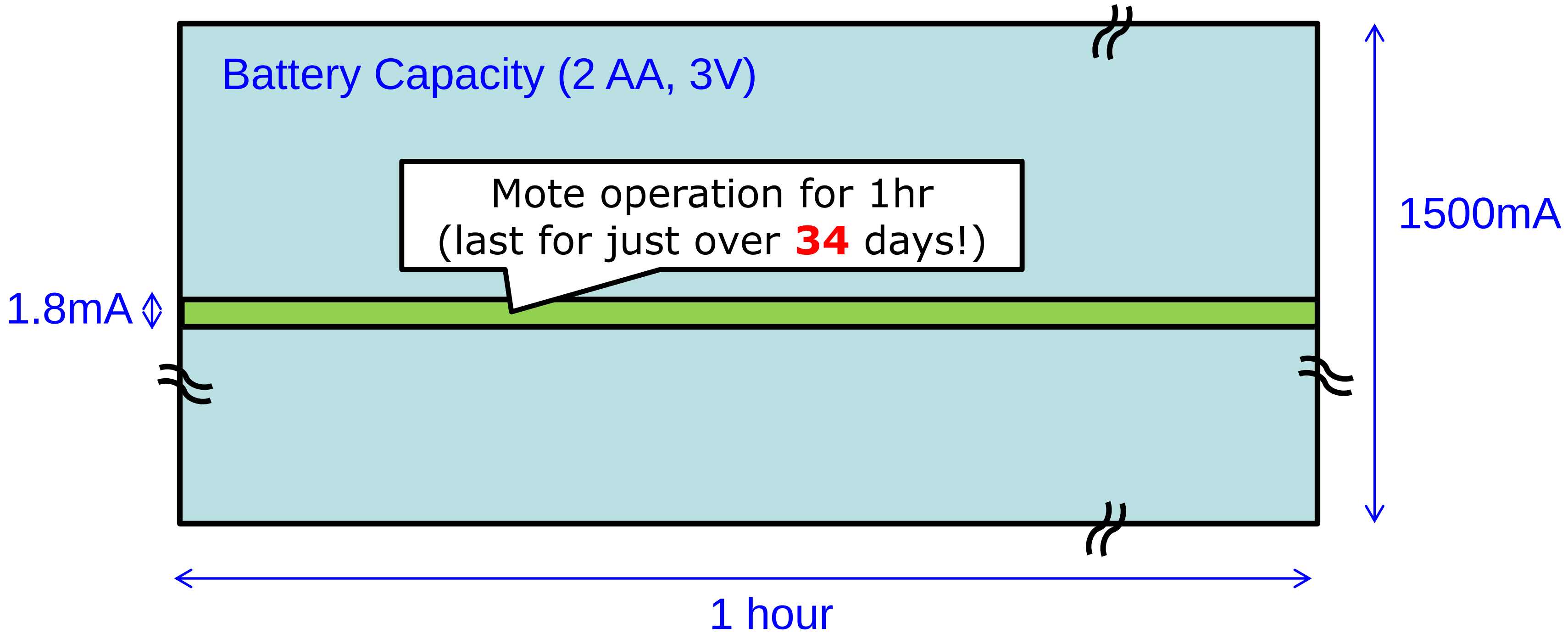
– Power Profile:

	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)

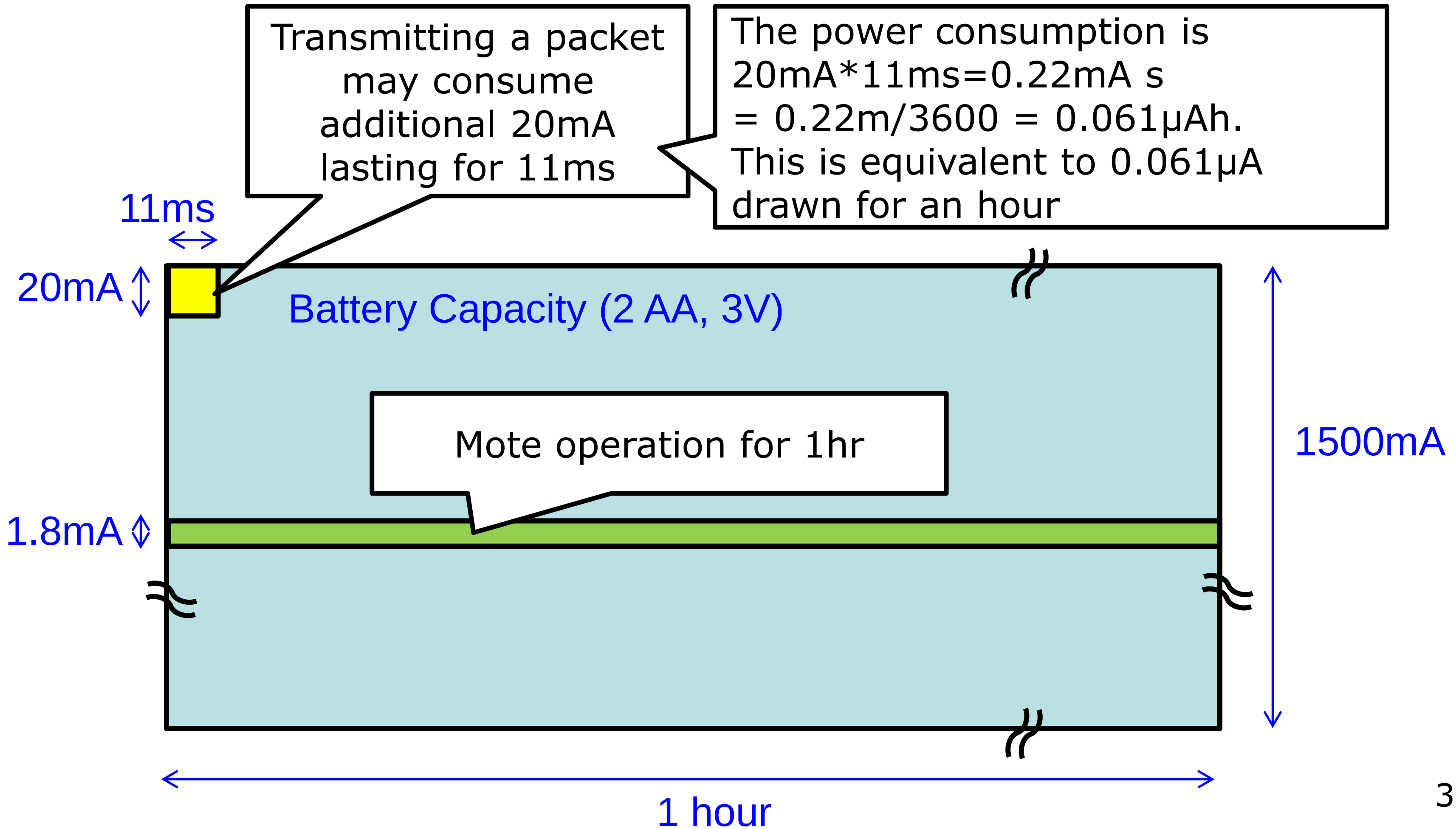
Power consumption map

– 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



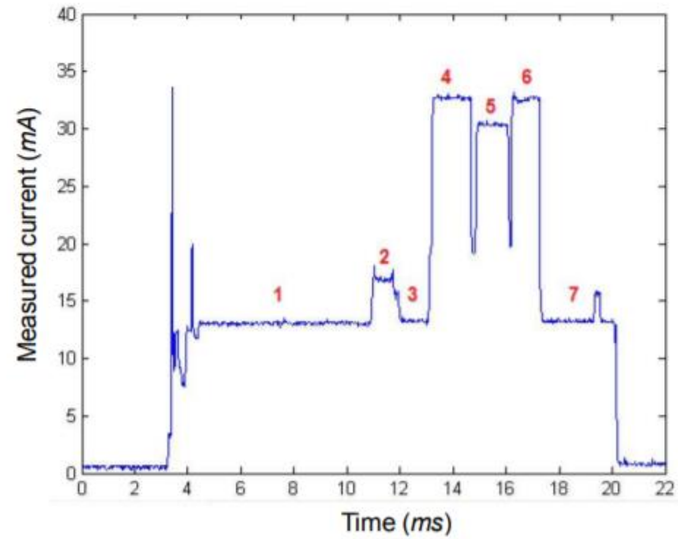
Power consumption (measured)

– 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



Exercise

A city council plans to improve its traffic flow at a busy junction. A smart traffic light is proposed.

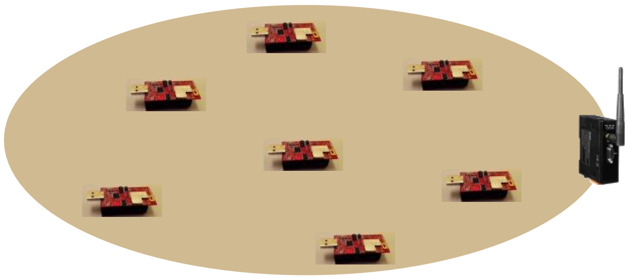
As an engineer, you are asked to lead the project to build the smart traffic light. What types of sensors will you consider to measure the traffic flow?

Solution

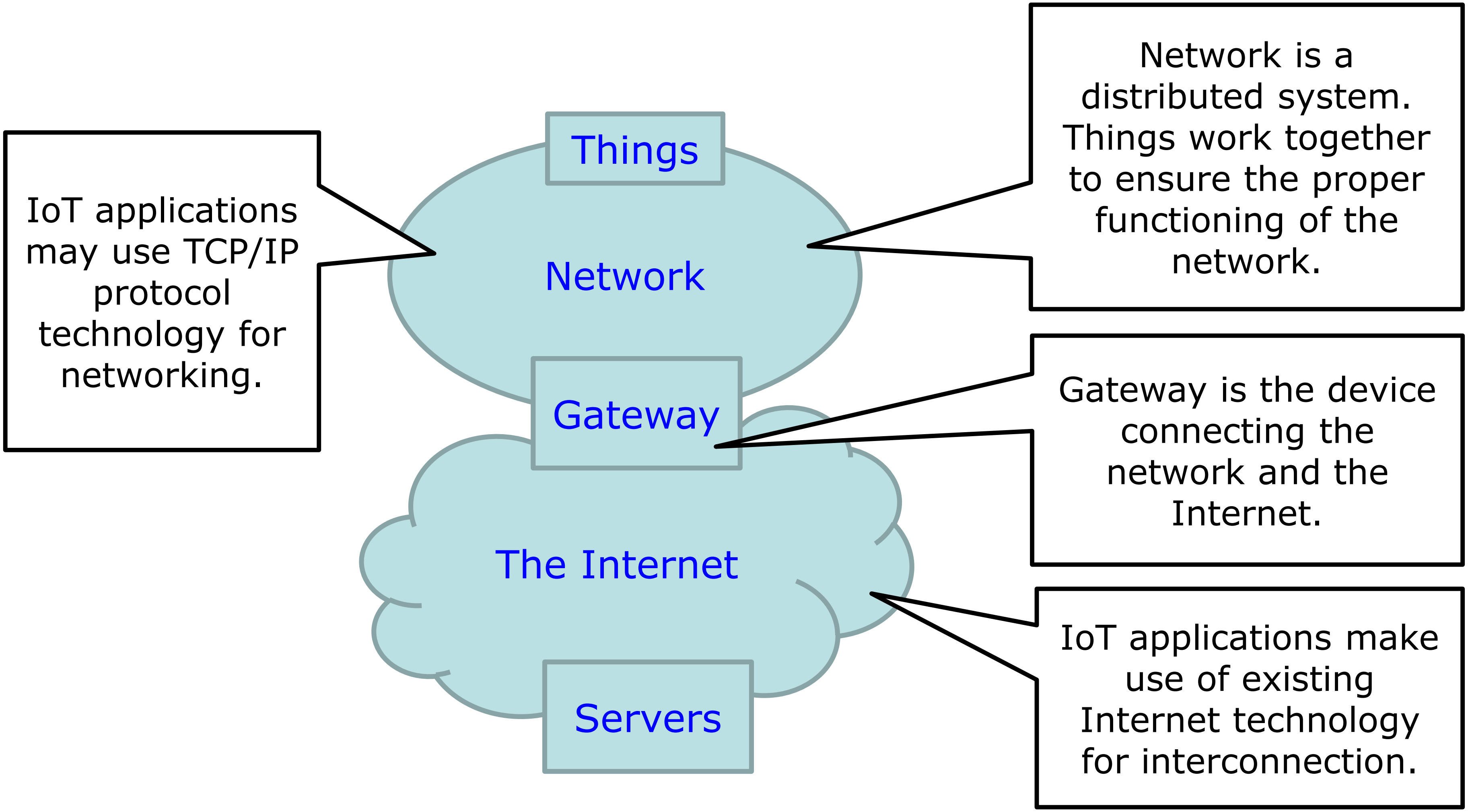
There are many options:

- Video Camera
- Pneumatic Road tube
- Piezoelectric Sensor
- Inductive Loop
- Magnetic Sensor
- Acoustic detector
- Passive Infrared
- Others (with appropriate argument)

Communication Architecture



IoT Networking



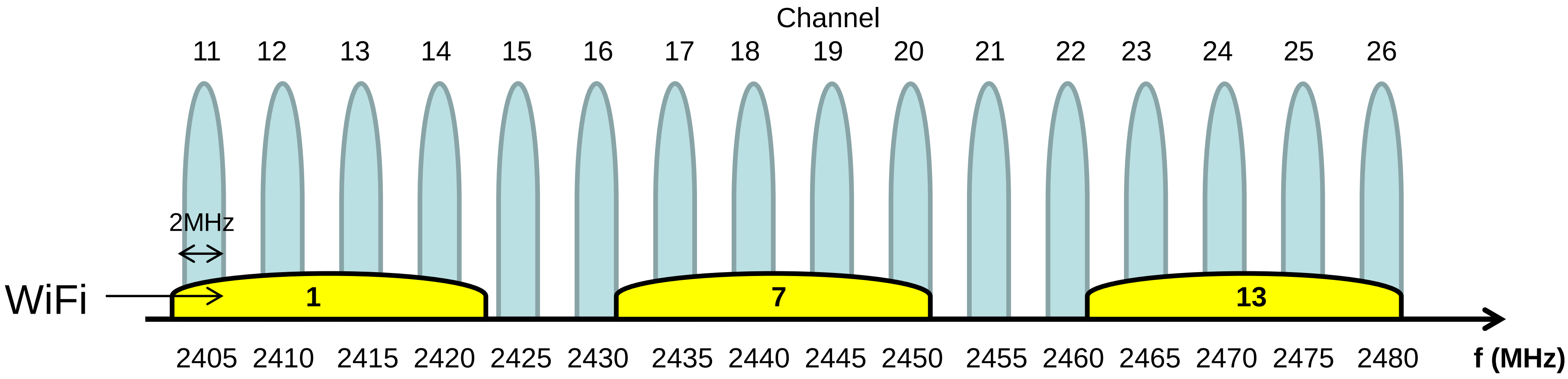
We focus on IEEE 802.15.4

IEEE 802.15.4 Standard

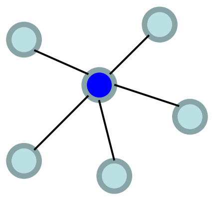
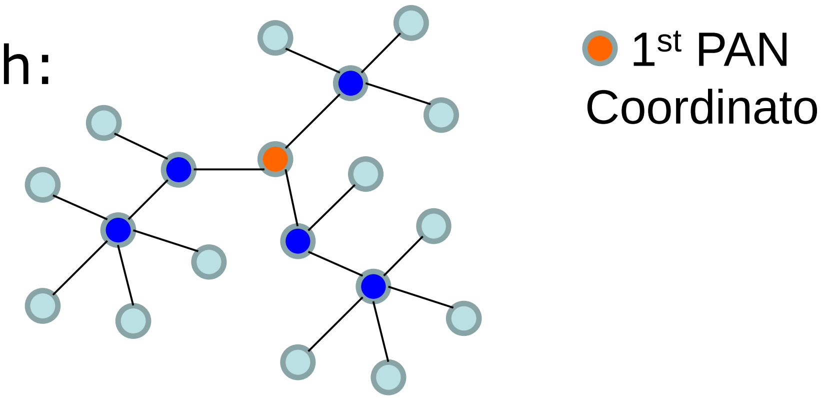
- IEEE 802.15.4 Standard specifies communication technologies for low-rate wireless personal area networks (LR-WPANs).
  - Including PHY & Medium Access Control (MAC)
- Three possible frequency bands (unlicensed):
  - 868.0-868.6 MHz, 902-928 MHz, <u>2.4-2.485 GHz</u>
- Maximum data rate: 250 kb/s
  - 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



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.

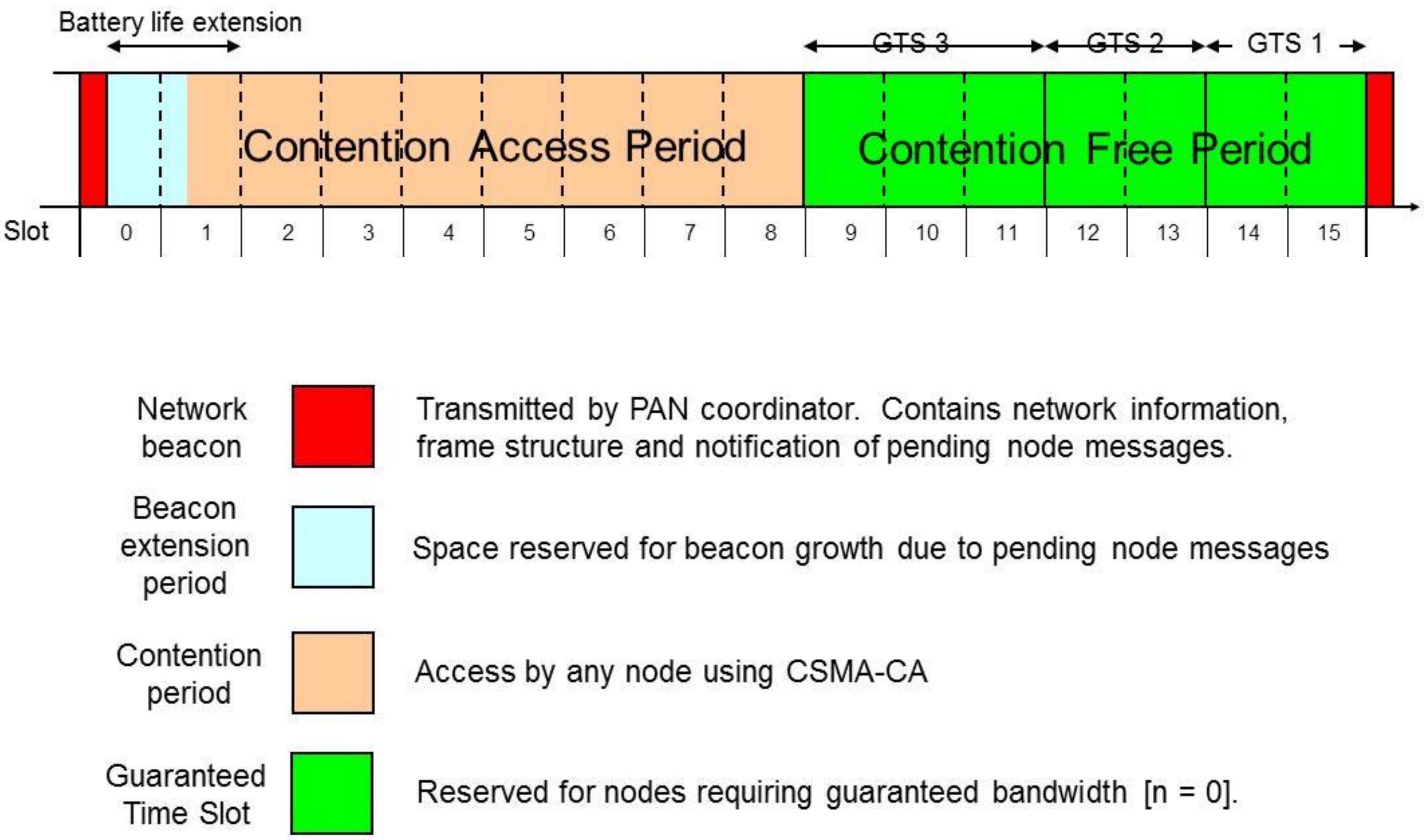
IEEE 802.15.4 MAC: Mode

- 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

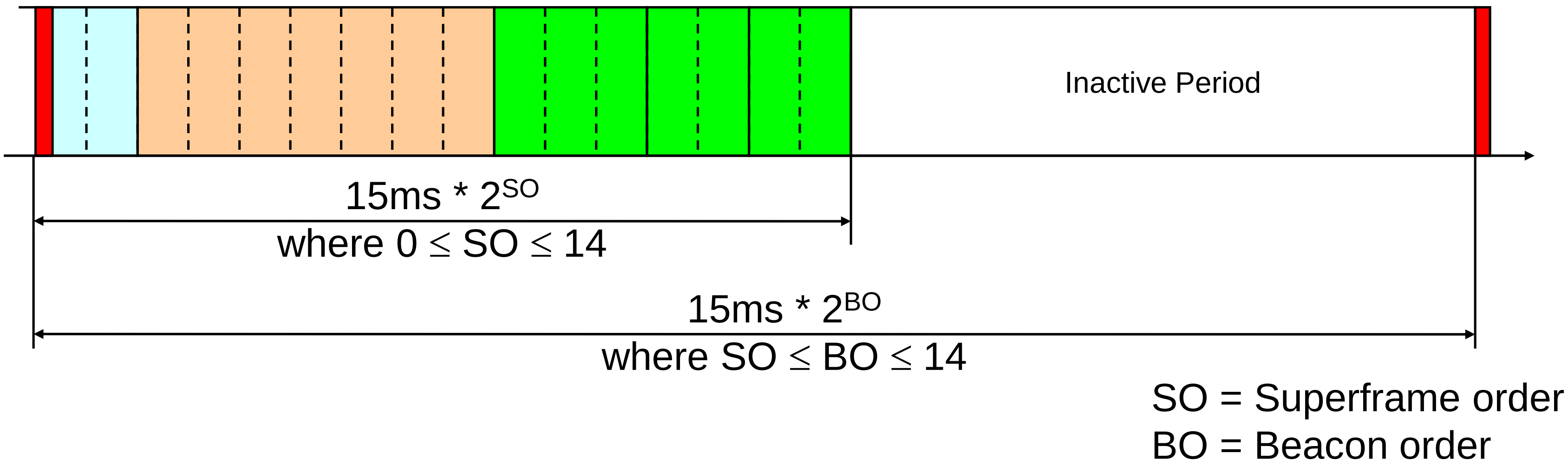
IEEE 802.15.4 MAC: Superframe

– Superframe (16 slots):



IEEE 802.15.4 MAC: Superframe

– Superframe Active/Inactive periods:



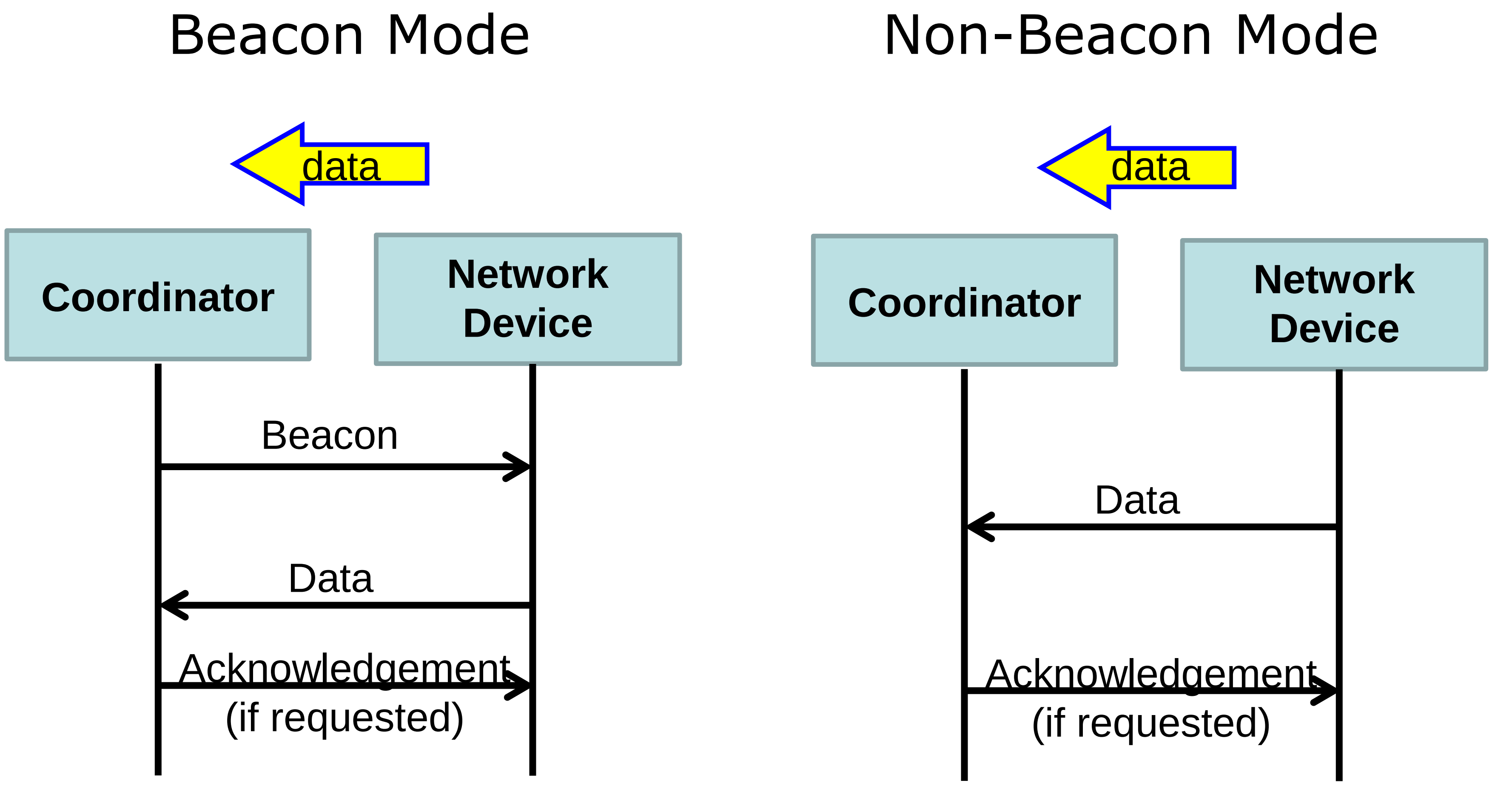
– All nodes can sleep during the inactive period

IEEE 802.15.4 MAC: Data Transfer

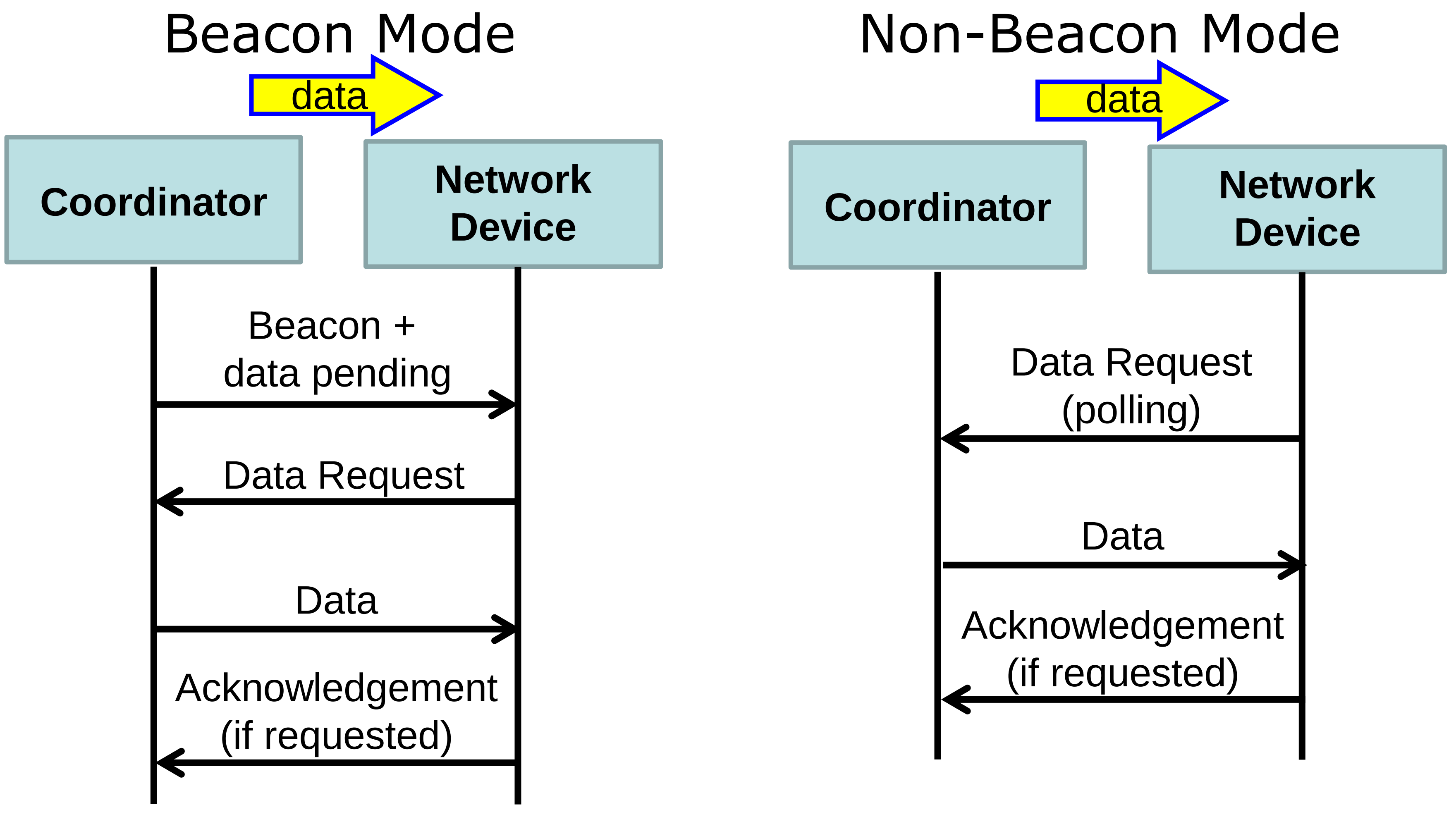
- Nodes use CSMA-CA to access the channel and transmit their data
  - Random delay is imposed to access an idle channel
  - In beacon-mode, all nodes are synchronized in time

- 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

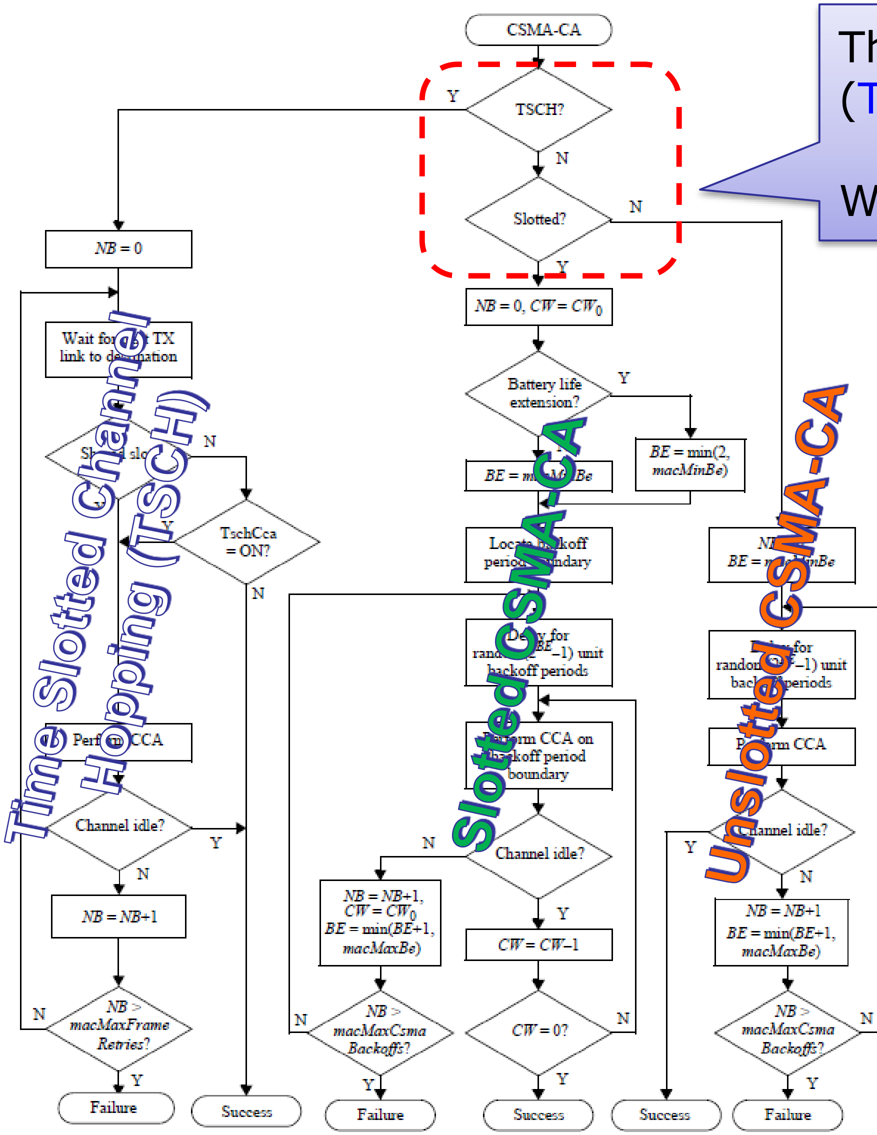
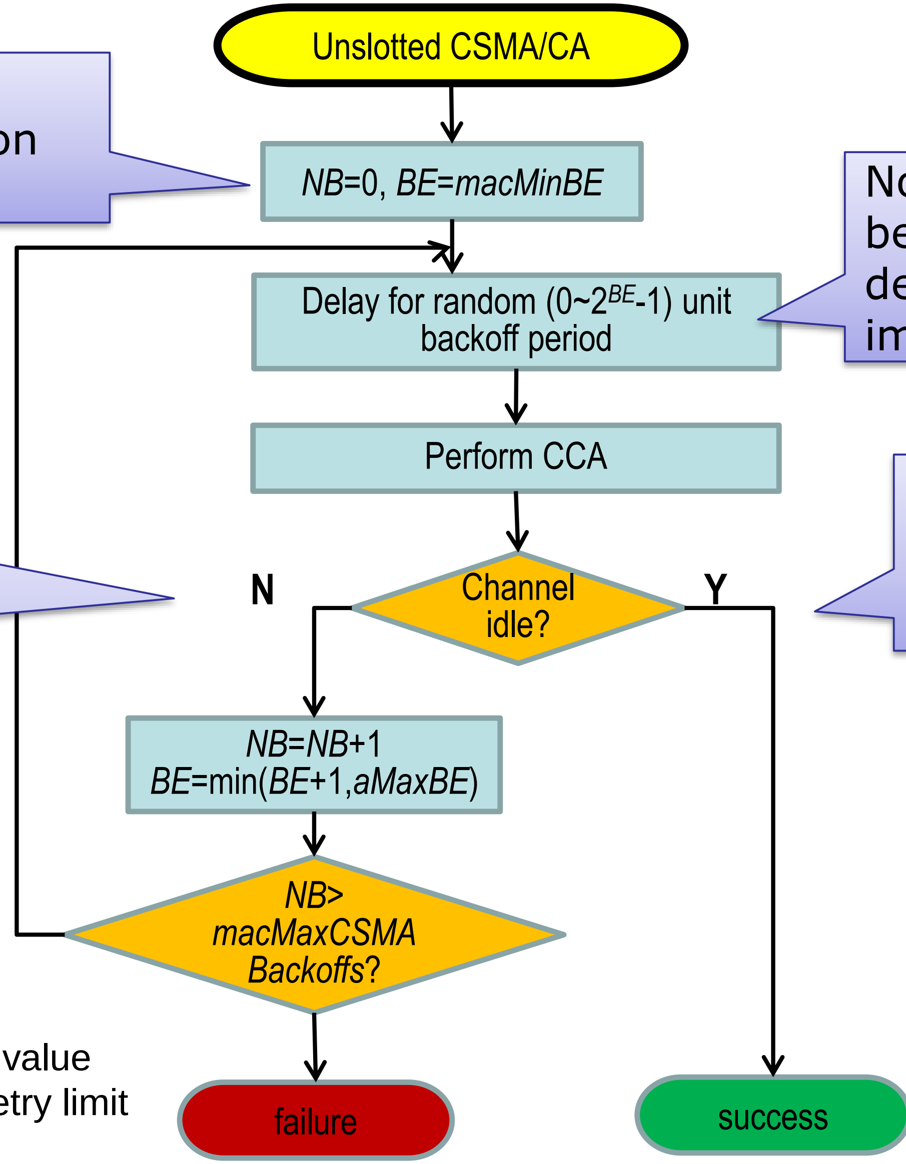


Figure 6-5—CSMA-CA algorithm

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

We focus on Slotted & Unslotted only.

IEEE 802.15.4 MAC: Unslotted CSMA/CA Channel Access



No battery life extension operation for BE

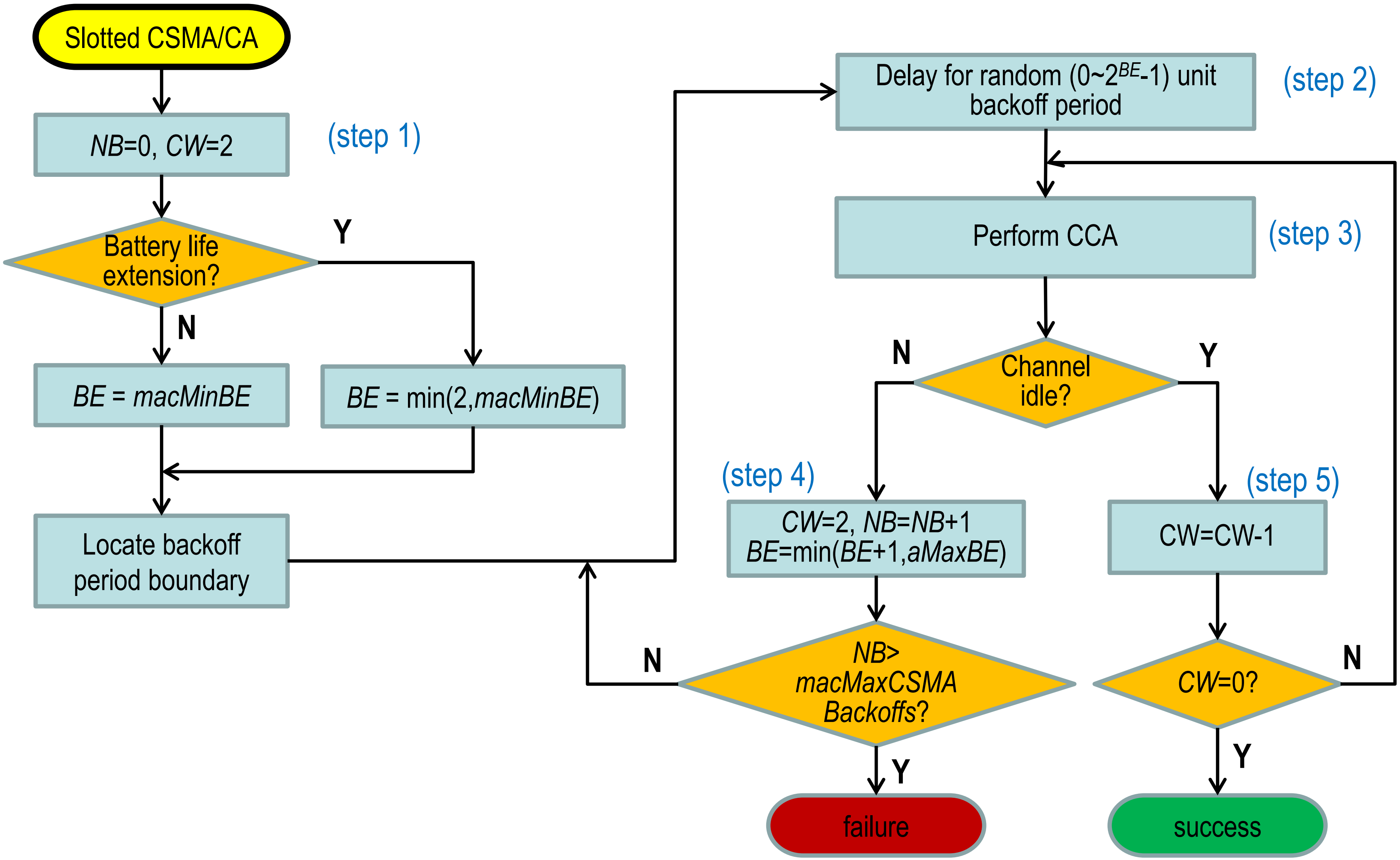
No need to wait for beacon, start the delay process immediately

Same operation as slotted CSMA/CA for busy channel

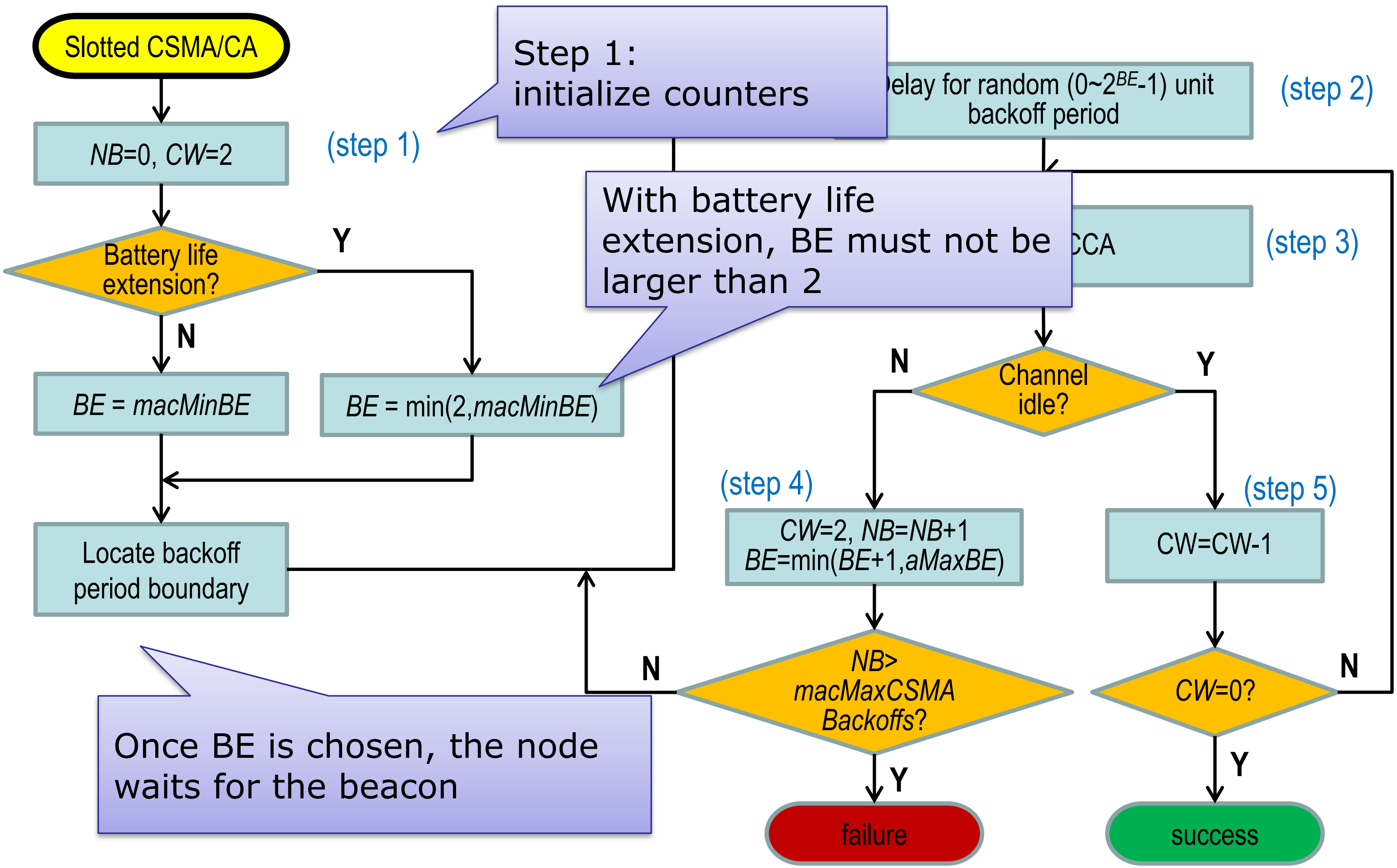
Transmit after CCA indicates idle channel

NB: Retry counter
BE: Backoff counter
macMinBE: Initial BE value
aMaxBE: Upper limit of BE value
macMaxCSMABackoffs: Retry limit

IEEE 802.15.4 MAC: CSMA/CA Channel Access



IEEE 802.15.4 MAC: CSMA/CA Channel Access

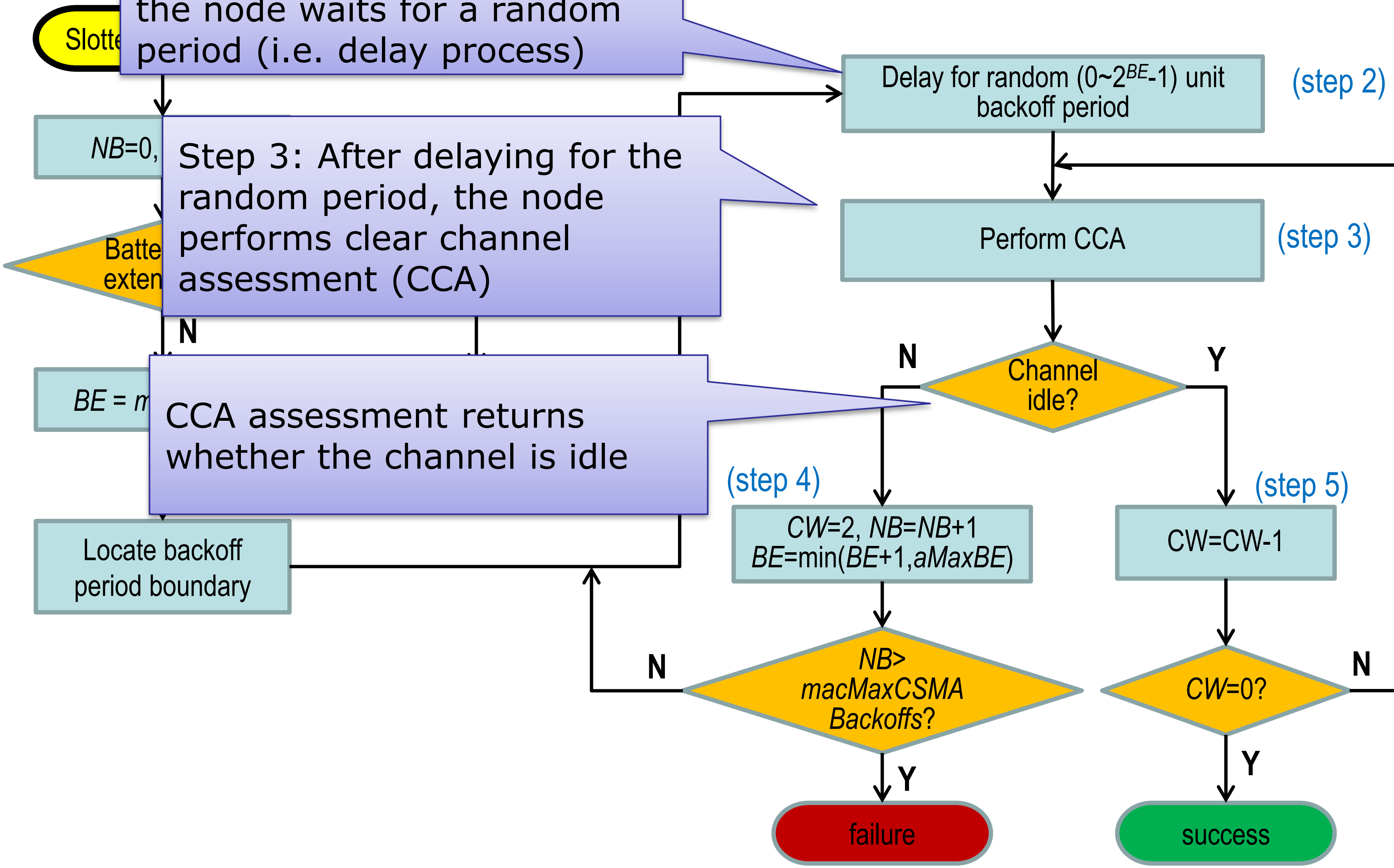


IEEE 802.15.4 MAC: CSMA/CA Channel Access

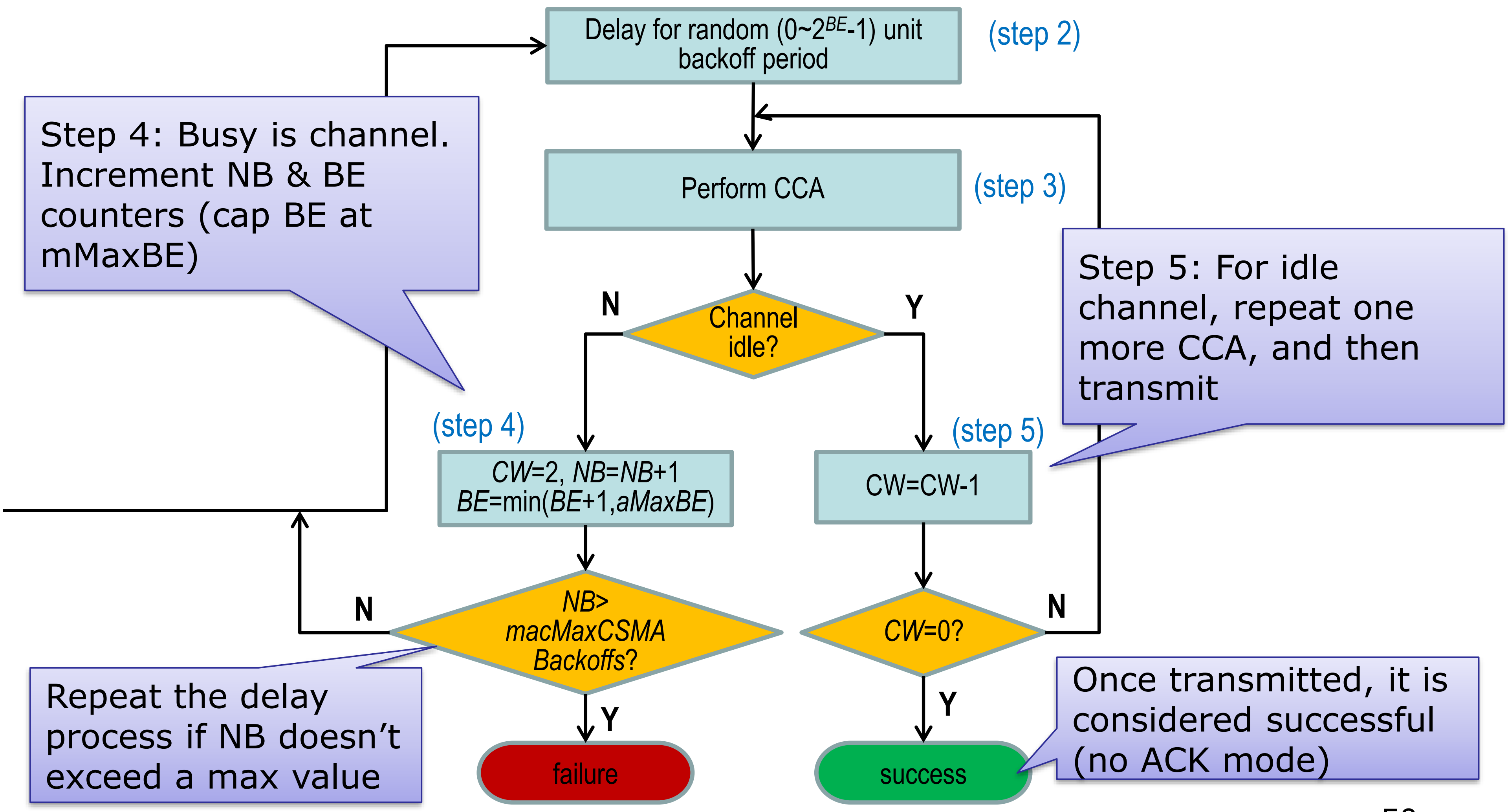
Step 2: Superframe detected, the node waits for a random period (i.e. delay process)

Step 3: After delaying for the random period, the node performs clear channel assessment (CCA)

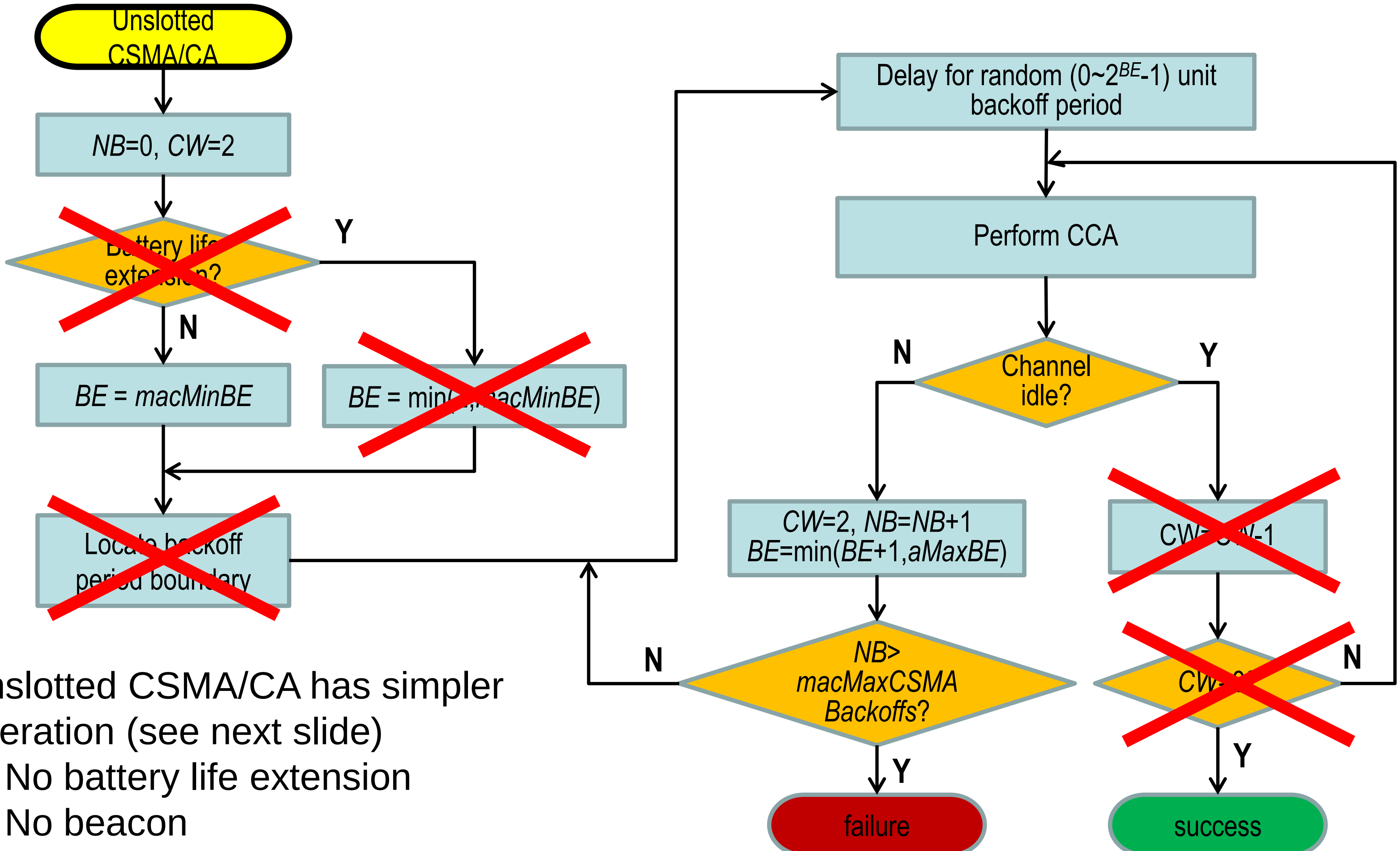
CCA assessment returns whether the channel is idle



IEEE 802.15.4 MAC: CSMA/CA Channel Access



IEEE 802.15.4 MAC:
Unslotted CSMA/CA Channel Access



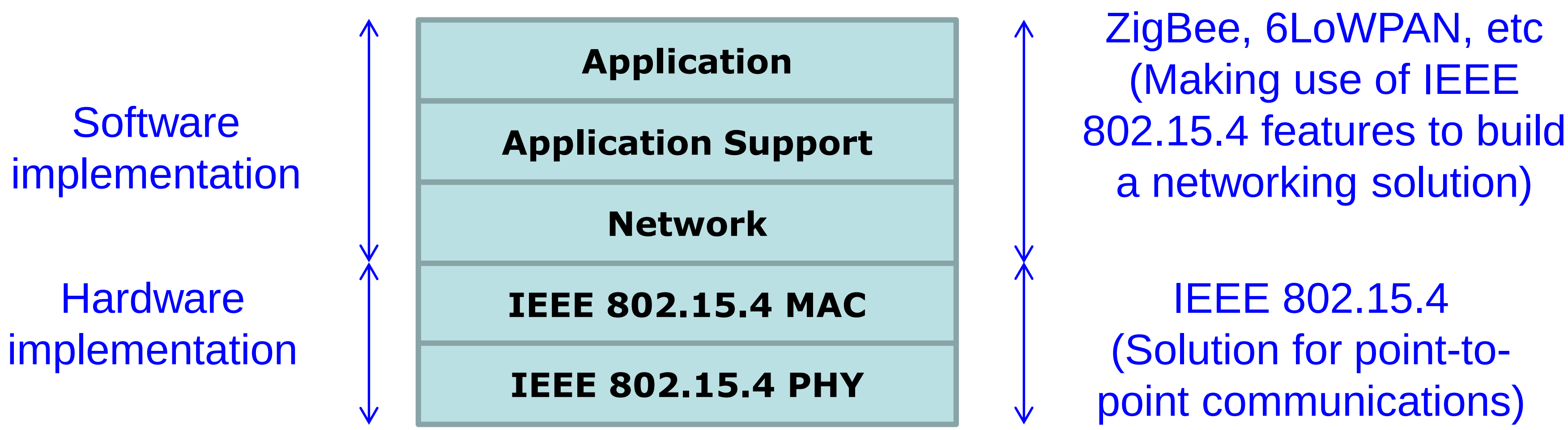
Unslotted CSMA/CA has simpler operation (see next slide)

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

IEEE 802.15.4 MAC: 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



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?