Cyber Physical Systems Workshop

WSCF 2019

Introduction to Wireless Sensor Networks

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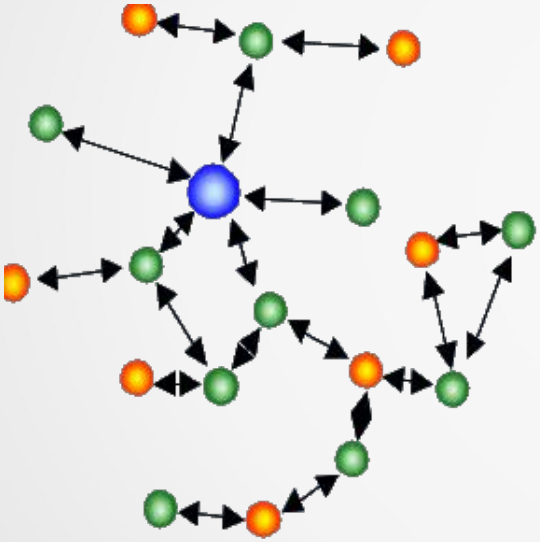
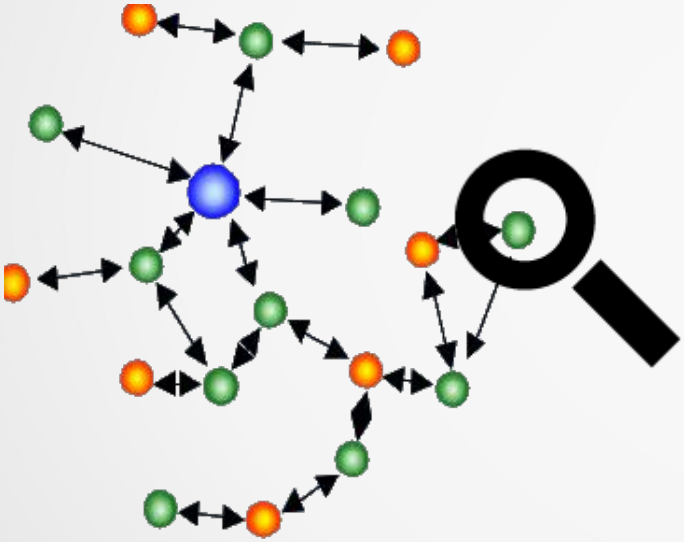
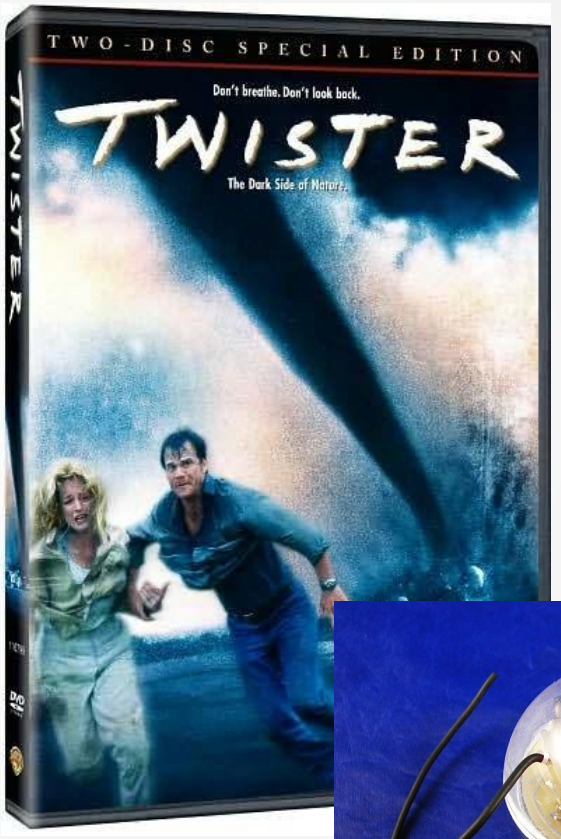
what are the wireless sensor networks?



- WSN
  - Wireless
  - Sensor (& actuators)
  - Network

WSN: from fiction to reality

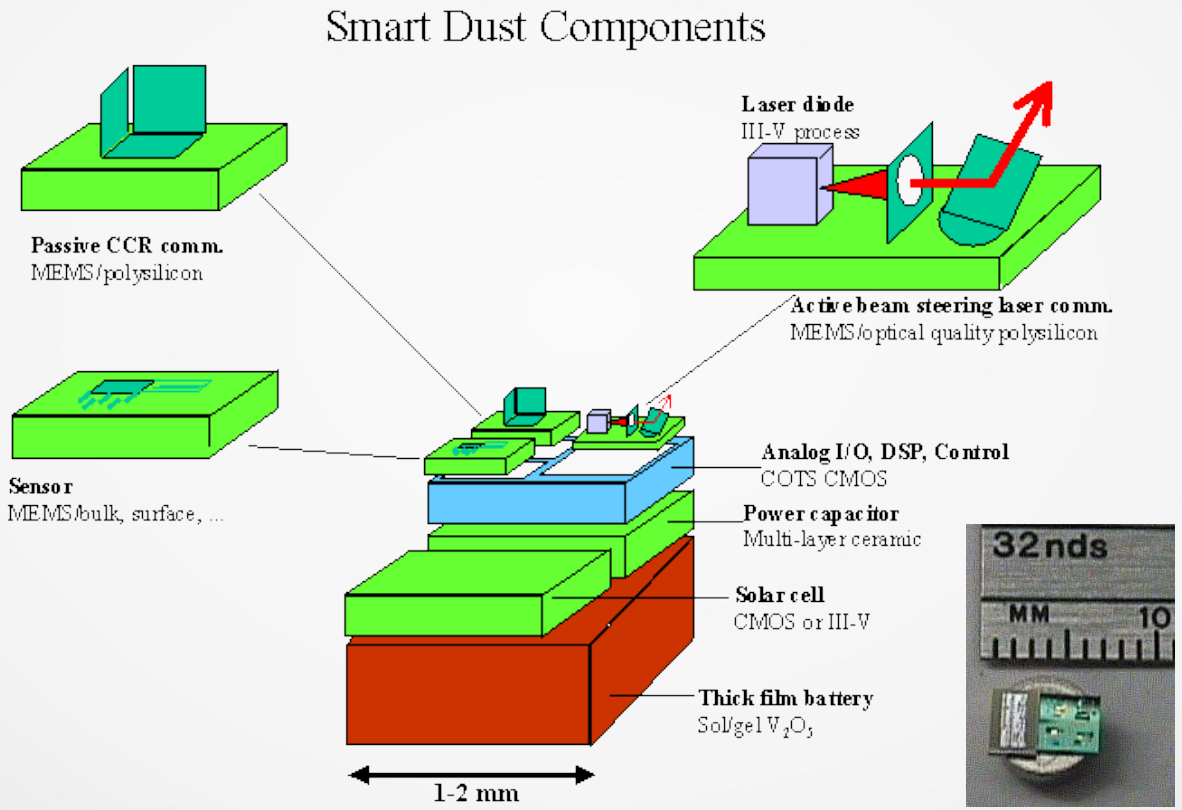




Twister (1996)

Wireless Sensor Networks (WSN): begin

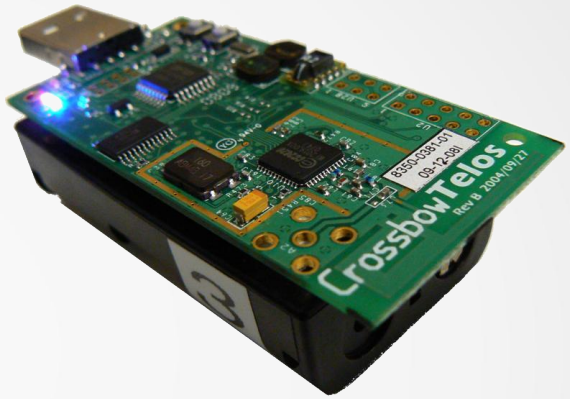
"smart dust" (~2000)



Fuente: http://robotics.eecs.berkeley.edu/~pister/SmartDust/

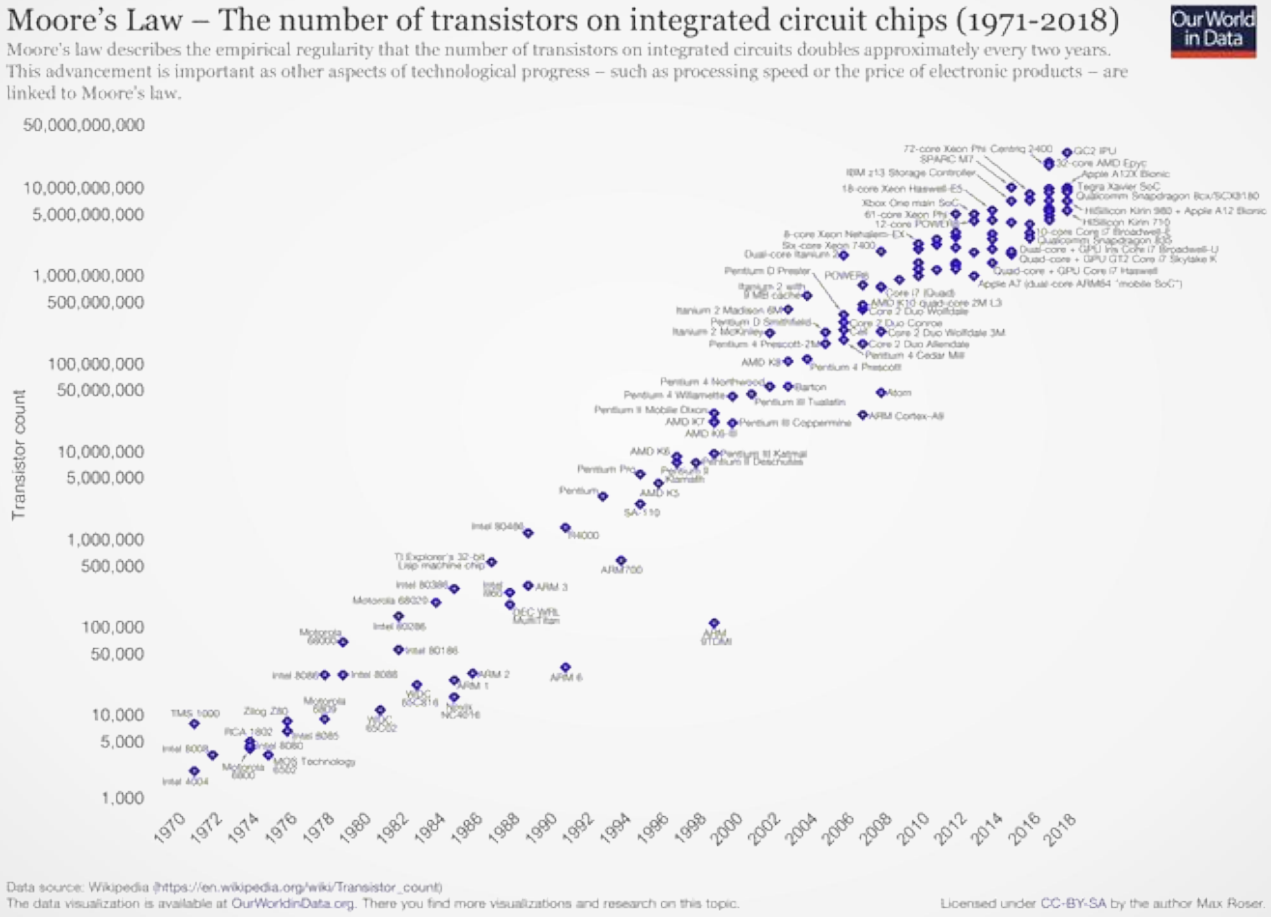
WSN: reality today

- **TelosB /sky (2005)**
  - MSP430F1611 (8 MHz)
    - 10 KB RAM
    - 48 KB Flash
    - 4mA active / 10 uA sleep
  - CC2420 (transceiver 2.4 GHz)



- Benefits of moore's law?

Moore’s Law


Moore’s Law – The number of transistors on integrated circuit chips (1971-2018)
Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.
Our World in Data
Transistor count
50,000,000,000
10,000,000,000
5,000,000,000
1,000,000,000
500,000,000
100,000,000
50,000,000
10,000,000
5,000,000
1,000,000
500,000
100,000
50,000
10,000
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1970
1972
1974
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1978
1980
1982
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1986
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2004
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2008
2010
2012
2014
2016
2018
Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.
Licensed under CC-BY-SA by the author Max Roser.

WSN: reality today

- **TelosB /sky (2005)**
  - MSP430F1611 (8 MHz)
    - 10 KB RAM
    - 48 KB Flash
    - 4mA active / 10 uA sleep
  - CC2420 (transc. 2.4 GHz)
- **CCC2538 SoC (2013)**
  - Cortex M (32 MHz)
    - 32 KB RAM
    - 256 KB Flash
    - ~10 mA active / ~1uA sleep
  - “CC2520” integrated

- Benefits of moore's law?

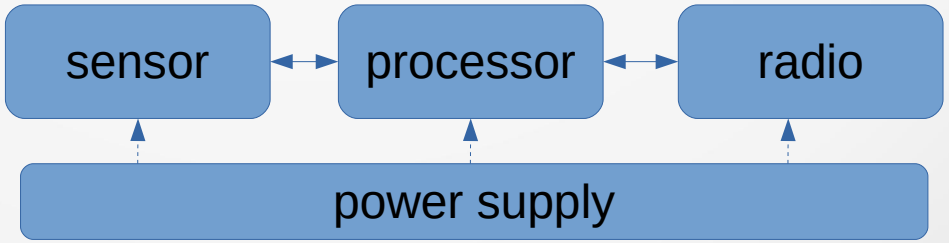
EMB-Z2538PA

IoT device / mote / sensor node

- Requirements
  - low ….

cost size consumption

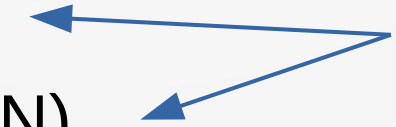
- Components



Communication technologies

Communication technologies

- LAN (Local)
- WLAN (Wireless Local)
- CAN (Campus)
- MAN (Metropolitan)
- WAN (Wide Area)
- **PAN** (Personal Area)
- W**PAN** (Wireless PAN)
- **LP**WAN (Low Power WAN)

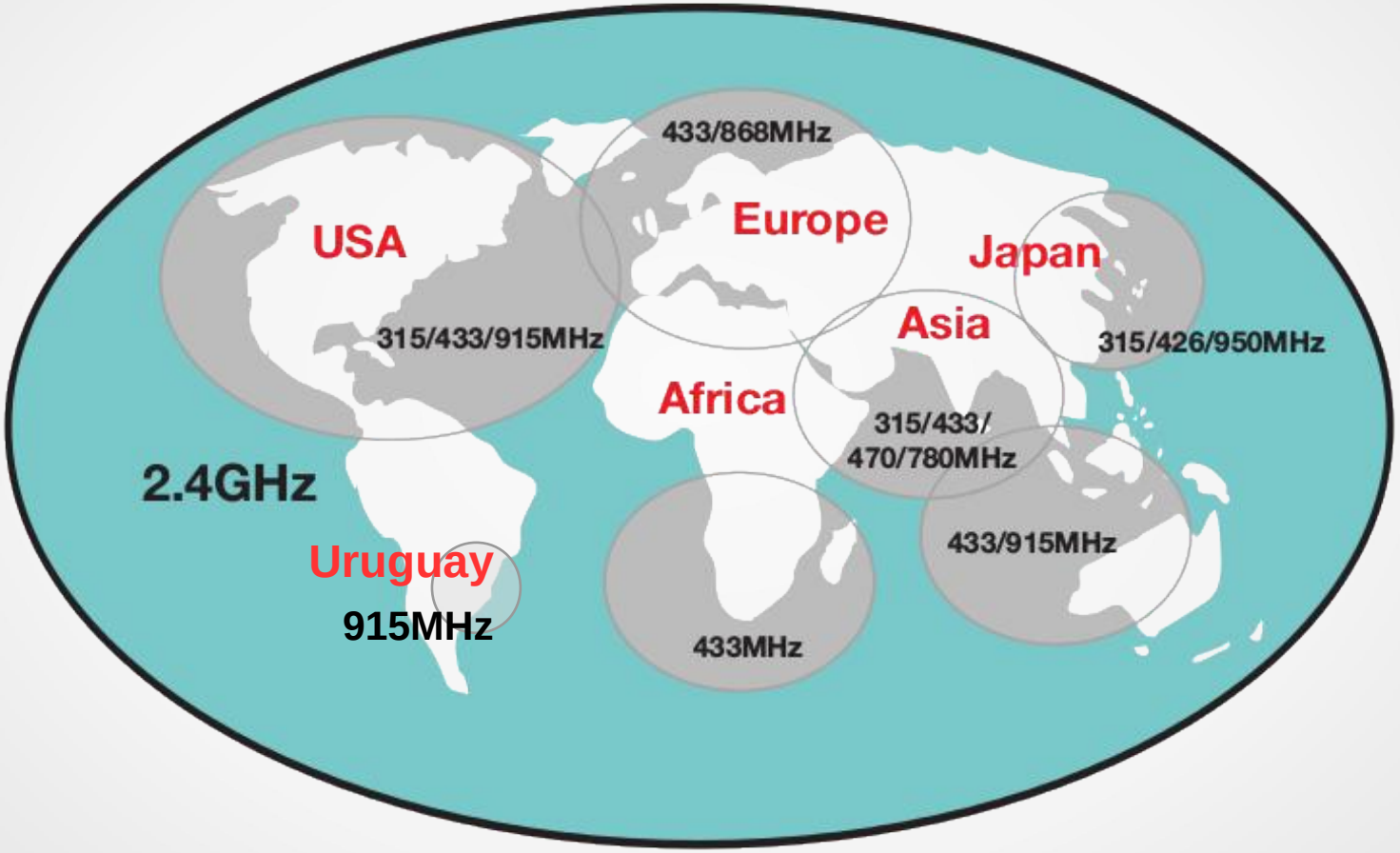


WSN

Technology menu

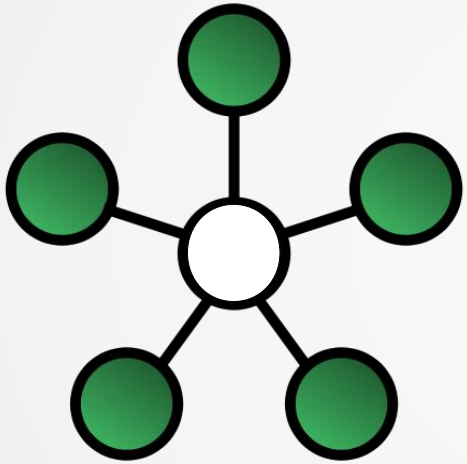
- LPWAN
  - SigFox
  - LoRa
  - Weightless/Telensa
  - RPMA/Ingenu
- Cell
  - NB-IoT
  - LTE-M
- WPAN
  - IEEE 802.15.4
    - 6lowpan
    - Zigbee
    - many others

Radio communication: ISM bands

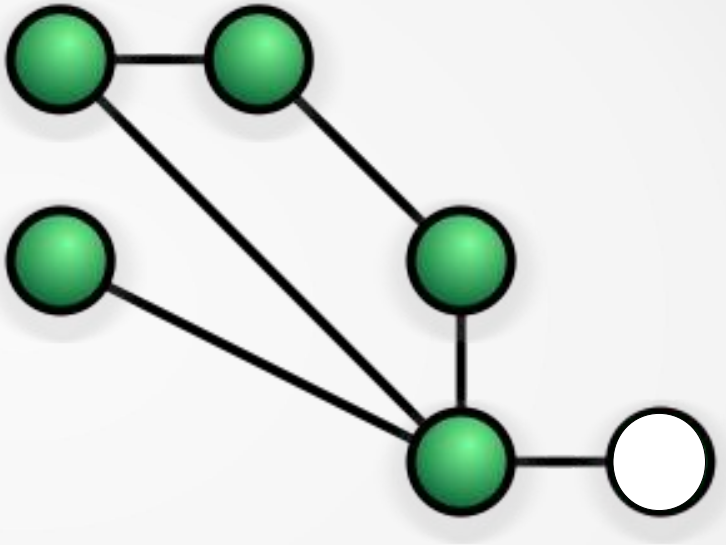


ISM: Industrial, Scientific and Medical

Differences: topology

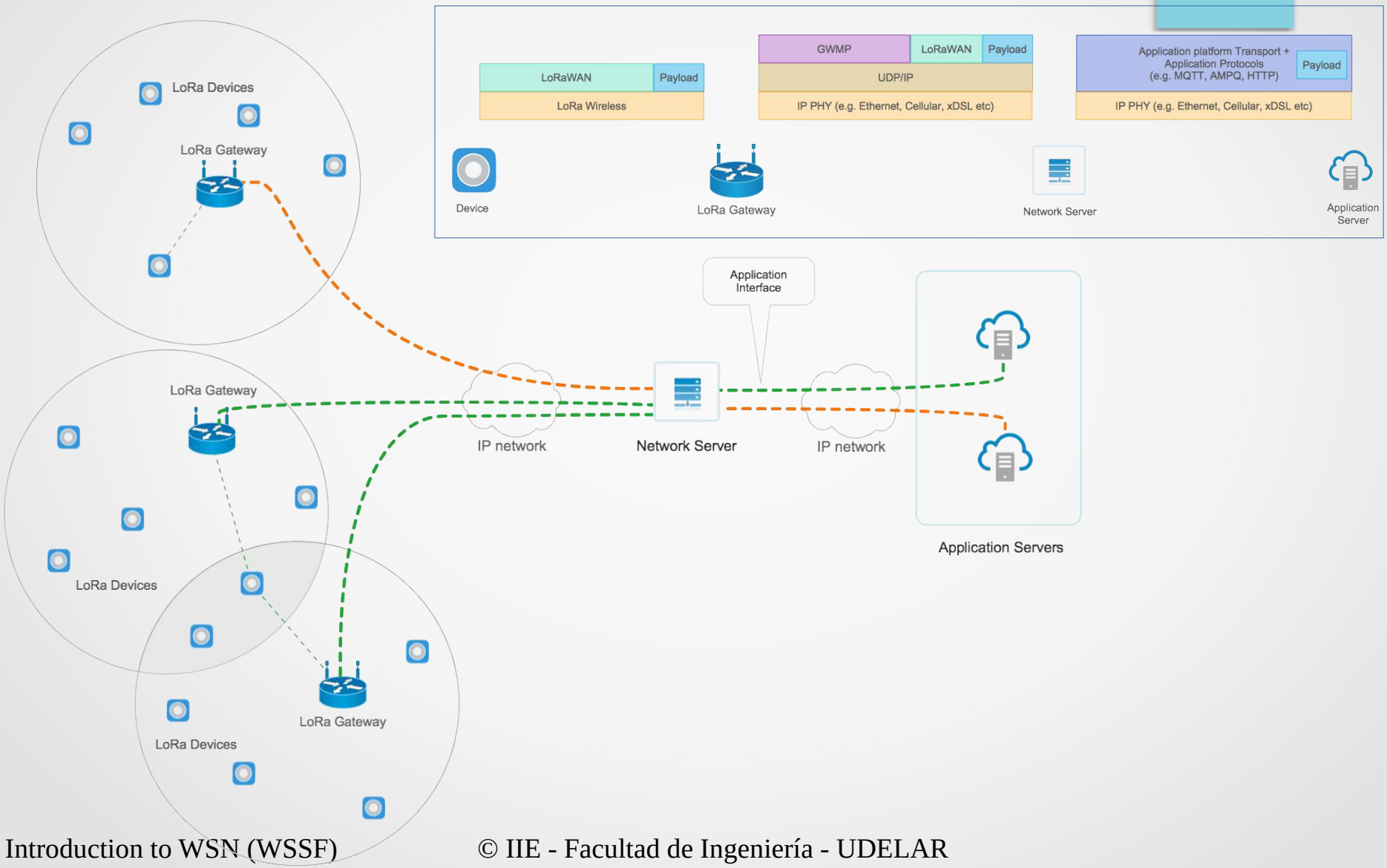


star

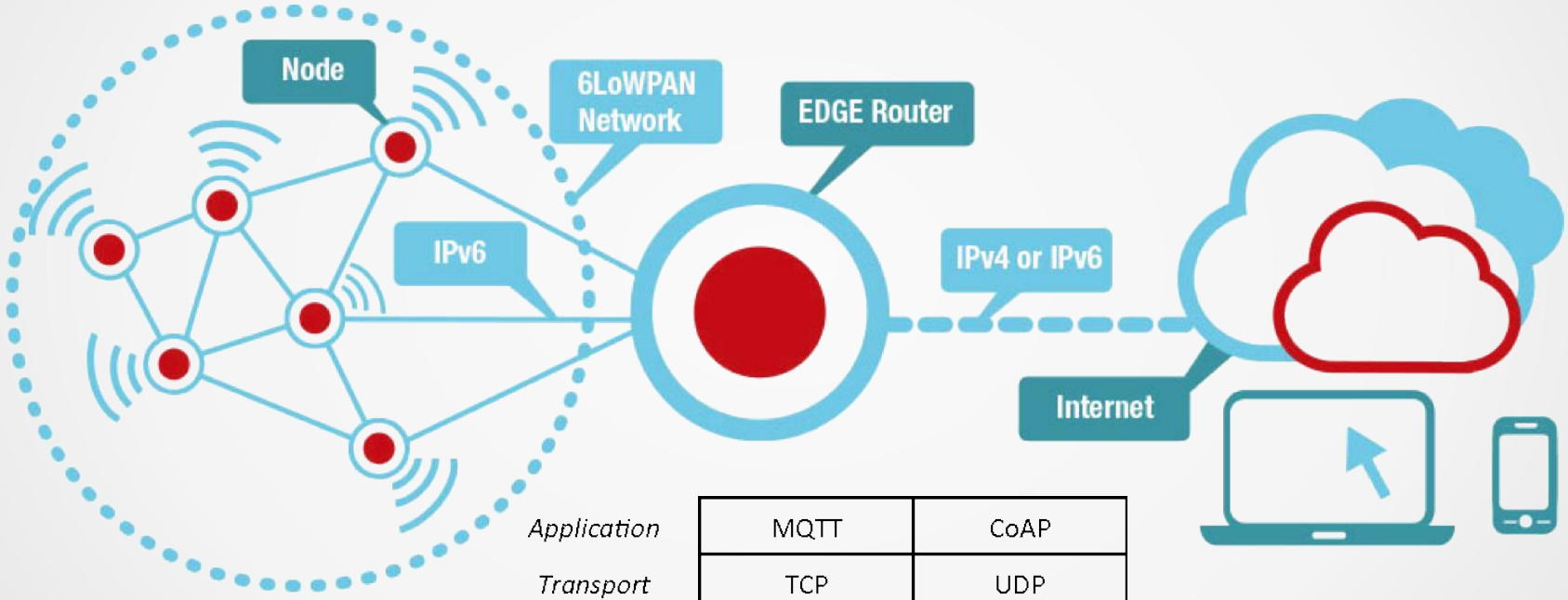


mesh

Star: LoRaWAN

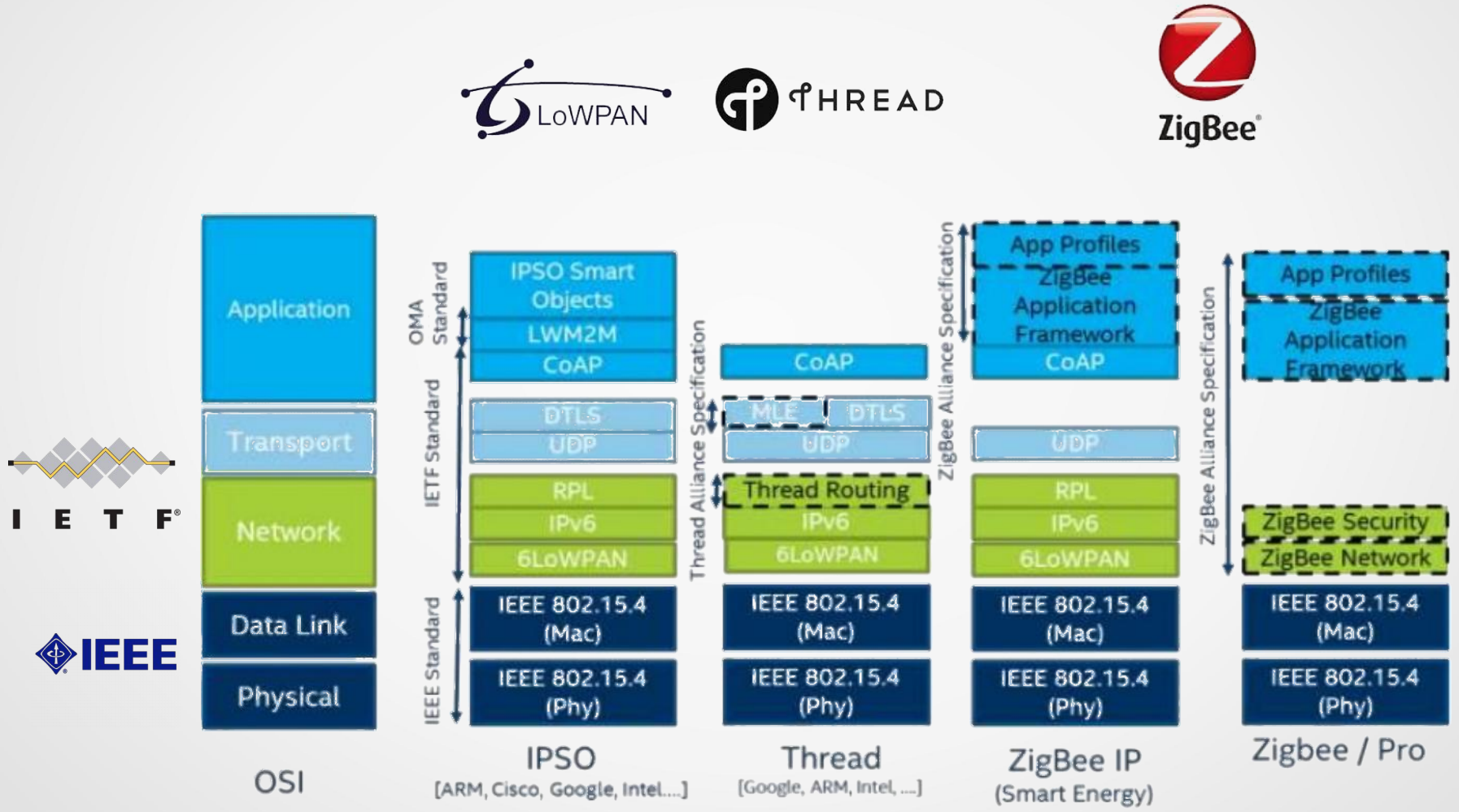


Mesh: IEEE 802.15.4 / 6lowpan



Application	MQTT	CoAP
Transport	TCP	UDP
Network	IPv6	
Adaptation	6LoWPAN	
Link *Physical*	IEEE 802.15.4	Bluetooth Low Energy

IEEE 802.15.4: stack options

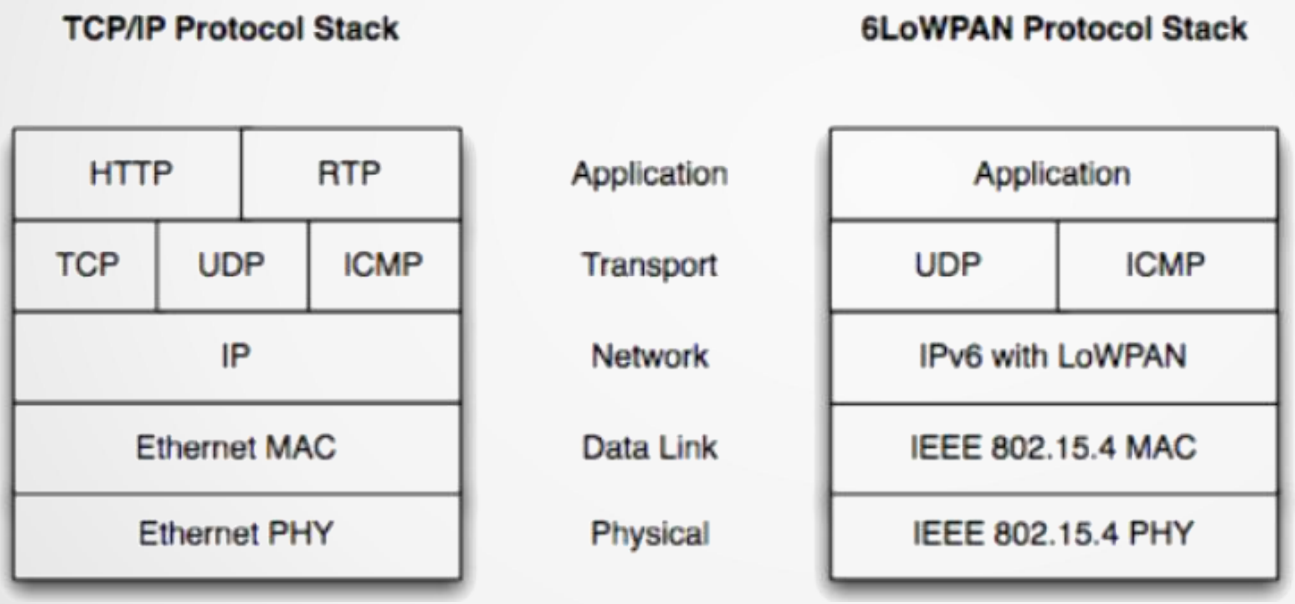


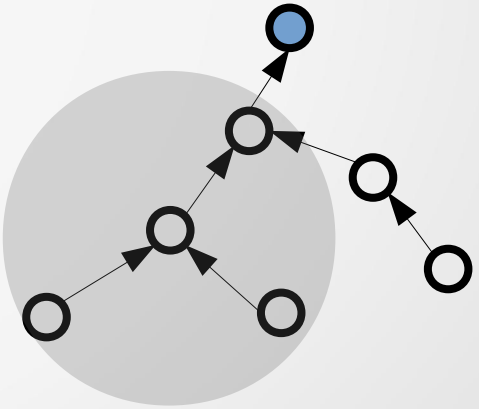
Outline

- More introduction
- “6LoWPAN stack”
  - IEEE 802.15.4 MAC
  - 6LoWPAN
  - RPL
  - CoAP
- Final thoughts

WSN: reference architecture

- TCP/IP versus 6loWPAN





Fuente: http://orbigo.net/2011/06/6lowpan-second-part-more-concepts-about-6lowpan/

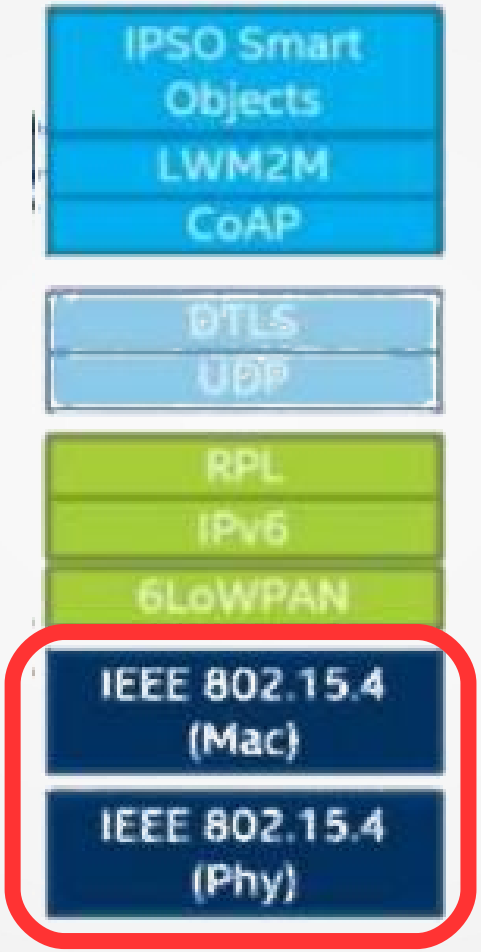
Standardization

- Technical standards:
  - agreements among the involved parties
- Aims and Benefits:
  - interoperability:
    - market competition and reduces vendor blockage
  - replication:
    - reuse technology (software & hardware)
    - best practices in different solutions

IEEE & IETF: as standardization bodies

- IEEE (Institute of Electrical and Electronics Engineers)
  - IEEE 802: family of IEEE standards
  - IEEE 802.**15** Working group **Wireless PAN**
  - IEEE 802.**15.4** Task Groups **Low Rate WPAN**
- IETF (Internet Engineering Task Force): WG (working groups)
  - **6LoWPAN**: IPv6 over Low power WPAN (concluded)
  - **6lo**: IPv6 over Networks of Resource-constrained Nodes
  - **6TiSCH**: IPv6 over the TSCH mode of IEEE 802.15.4e
  - **RoLL**: Routing over Low-power and Lossy networks
  - **CoRE**: Constrained RESTful Environments

IEEE 802.15.4 / 6LoWPAN stack

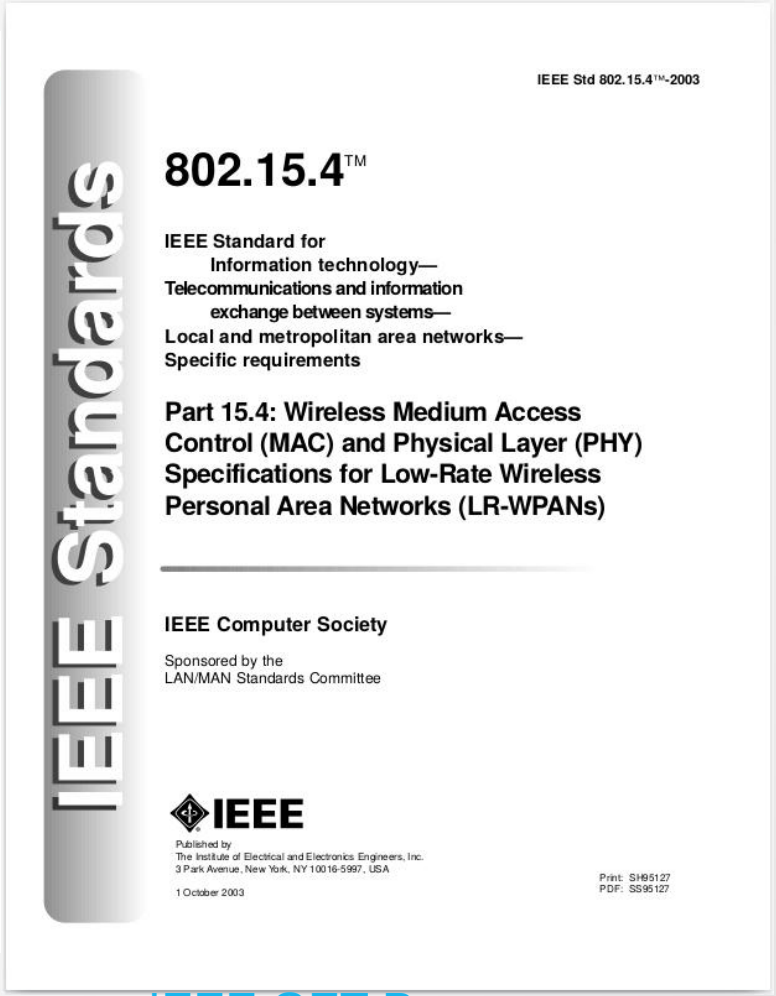


IEEE 802.15.4 PHY & MAC: funciones

- PHY
  - Tx & Rx data
  - ED: energy detection
  - RSSI: receive signal strength indicator
  - LQI: link quality indication
  - channel selection
  - CCA: clear channel assesment
- MAC
  - channel access
  - frame validation
  - acknowledged frame delivery
  - beacon management
  - GTS management
  - etc.

IEEE Std 802.15.4™-2015

- LR-WAN (Low Rate WPAN), spec.:
  - PHY: physical layer
  - MAC: medium access control
- versions: 2003, 2006, 2011, 2015
- amendment:
  - added to version 2015, e.g:
    - 802.15.4e-2012
    - 802.15.4g-2012
  - existing (to be added):
    - 802.15.4q-2016 (ULP PHY)



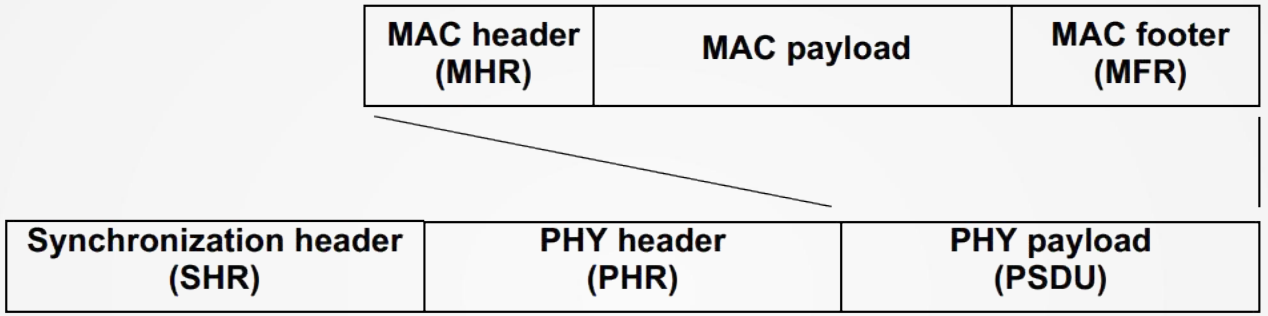
IEEE GET Program

IEEE 802.15.4 PHY

- Band and channels
- Initially (2003)
  - channel freq. identified by number
  - limited to 27 channel
  - three fixed options
- Since IEEE 802.15.4-2006
  - channel pages: scale
- Channel pages:
  - 0: defined in 2003 (1)
  - 1: optional in 2006 (2)

Page	Num.	Description
0 (1)	0	868 MHz band (BPSK)
	1–10	915 MHz band (BPSK)
	11–26	2.4 GHz band (O-QPSK)
1 (2)	0	868 MHz band (ASK)
	1–10	915 MHz band (ASK)
	11–26	Reserved
2	0	868 MHz band (O-QPSK)
	1–10	915 MHz band (O-QPSK)
	11–26	Reserved
3	0-13	2450 MHz (CSS)
4	0	sub-GHz band for UWB
	1-4	low band for UWB PHY
	5-15	high band for UWB PHY
5	0-3	780 MHz band (O-QPSK)
	4-7	780 MHz band (MPSK)
6	0-9	950 MHz band (BPSK)
	10-21	950 MHz band (GFSK)
7-31	Reser.	Reserved

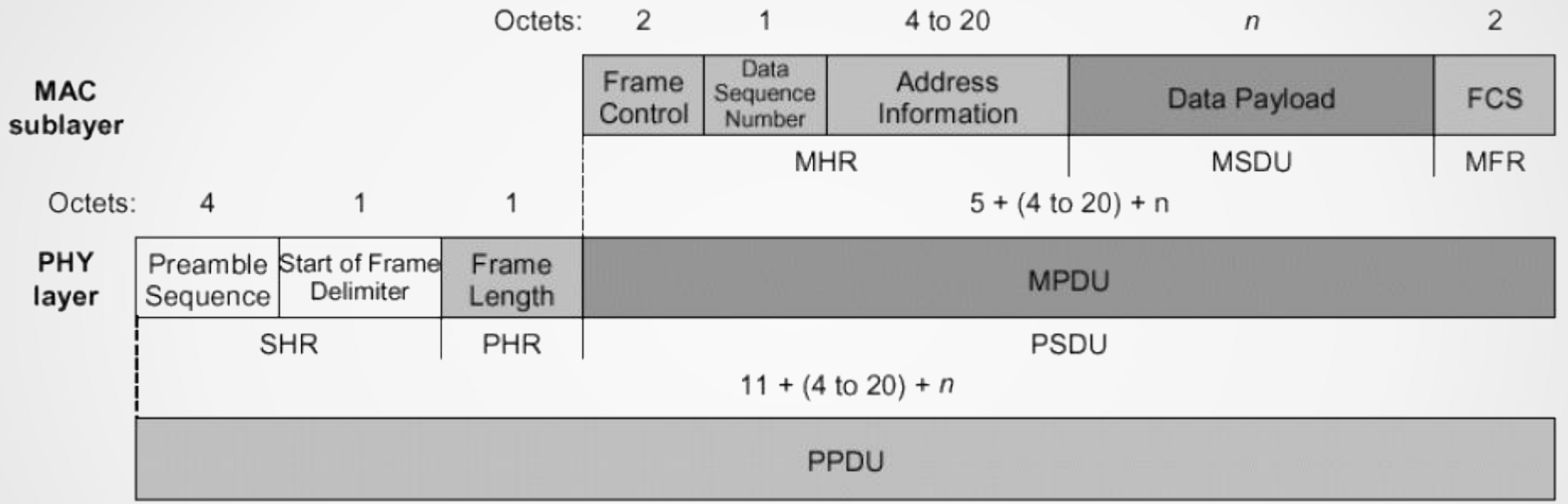
IEEE 802.15.4 PHY & MAC: frames



"IEEE standard for Low-Rate wireless networks," IEEE Std 802.15.4-2015, pp. 53, Apr. 2016.

- PHY service data unit (PSDU) <=> MAC frame

IEEE 802.15.4: frame format



M: MAC
P: PHY

X

PDU: **protocol** data unit
SDU: **service** data unit

=

MSDU: MAC service data unit
MPDU: MAC protocol data unit
PSDU: PHY service data unit
PPDU: PHY protocol data units

Frame format (version 1, 2006)

Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Destination PAN Identifier	Destination Address	Source PAN Identifier	Source Address	Auxiliary Security Header	Frame Payload	FCS
		Addressing fields						
MHR							MAC Payload	MFR

Bits: 0–2	3	4	5	6	7–9	10–11	12–13	14–15
Frame Type	Security Enabled	Frame Pending	AR	PAN ID Compression	Reserved	Dest. Addressing Mode	Frame Version	Source Addressing Mode

"IEEE standard for Low-Rate wireless networks," IEEE Std 802.15.4-2006, Sept. 2006.

Frame format (version 1, 2006)

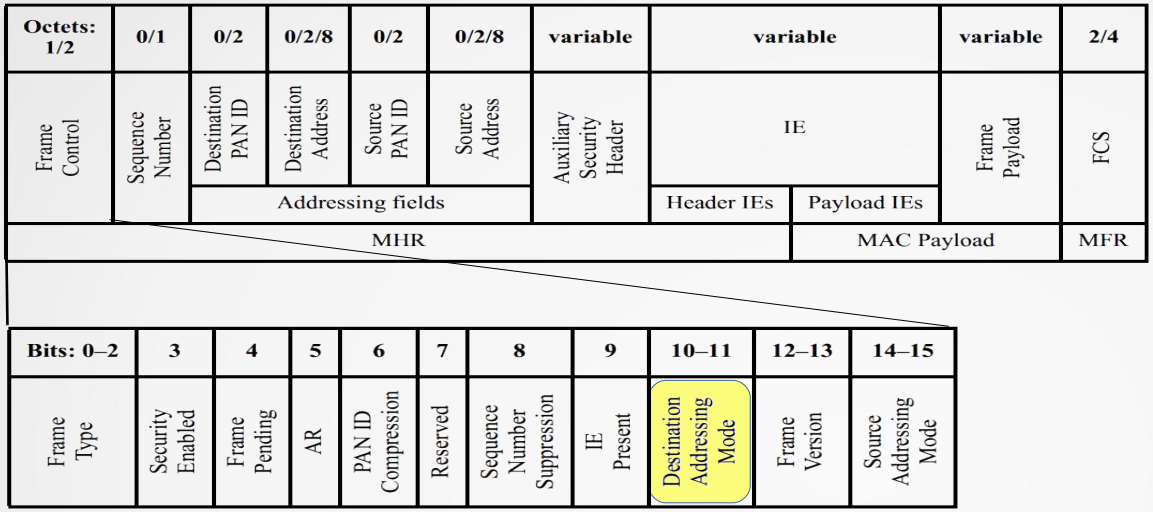
Octets: 2	1	0/2	0/2/8	0/2	0/2/8	0/5/6/10/14	variable	2
Frame Control	Sequence Number	Destination PAN Identifier	Destination Address	Source PAN Identifier	Source Address	Auxiliary Security Header	Frame Payload	FCS
		Addressing fields						
MHR							MAC Payload	MFR

Bits: 0–2	3	4	5	6	7–9	10–11	12–13	14–15
Frame Type	Security Enabled	Frame Pending	AR	PAN ID Compression	Reserved	Dest. Addressing Mode	Frame Version	Source Addressing Mode

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

"IEEE standard for Low-Rate wireless networks," IEEE Std 802.15.4-2006, Sept. 2006.

Addressing



Addressing mode value b1 b0	Description
00	PAN ID and address fields are not present.
01	Reserved
10	Address field contains a short address (16 bit).
11	Address field contains an extended address (64 bit).

Frame types: Data & ACK

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**

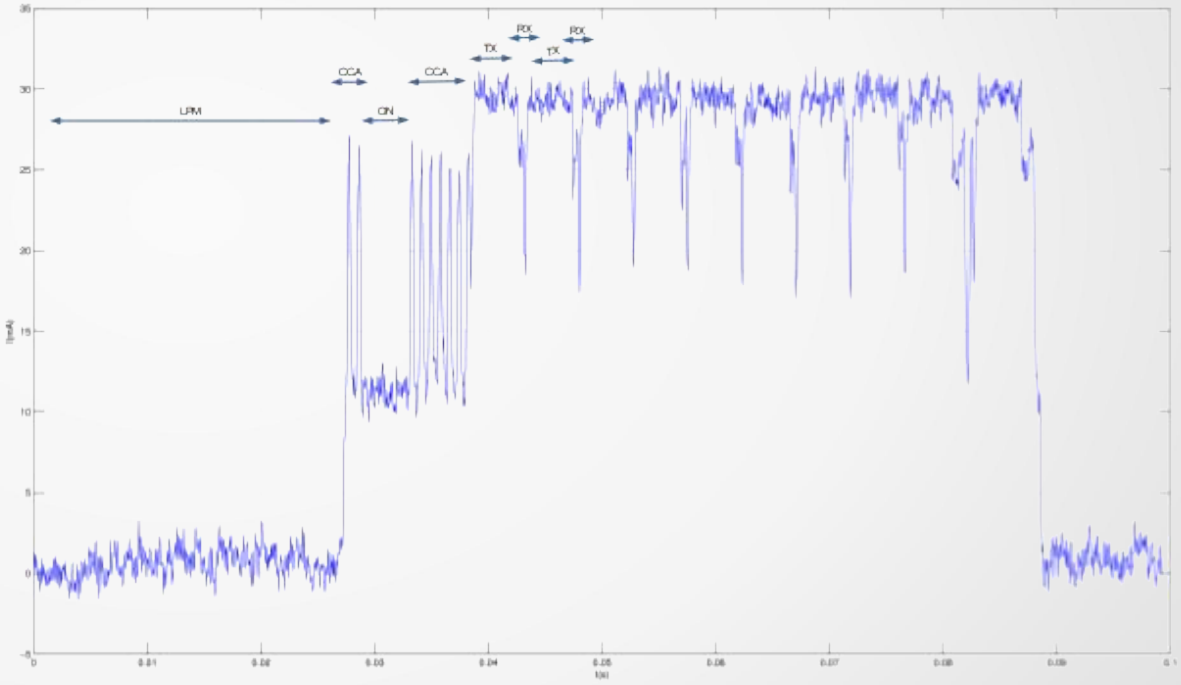
IEEE 802.15.4: MAC

MAC: medium access control

- Challenges
  - shared medium
  - interference
  - packet losses
- Requirements
  - as usual:
    - high throughput, low overhead, low error rates, …
  - added:
    - energy-efficient → radio duty-cycle

MAC: power consumption

- Power / Energy electrical consumption
  - Tx: expensive
  - Rx: also expensive
  - CCA (listening): also but less



State	$I_{avg}(mA)$
ON	11.23
TX	29.64
RX	24.17
CCA	21.64

MAC: energy efficiency

- Source of energy waste:
  - Collisions
  - Overhearing
  - Idle listening
  - Protocol overhead
- Generally:
  - The **simplest solution** is the **best**

“Super” frames structures

- Beacon superframe

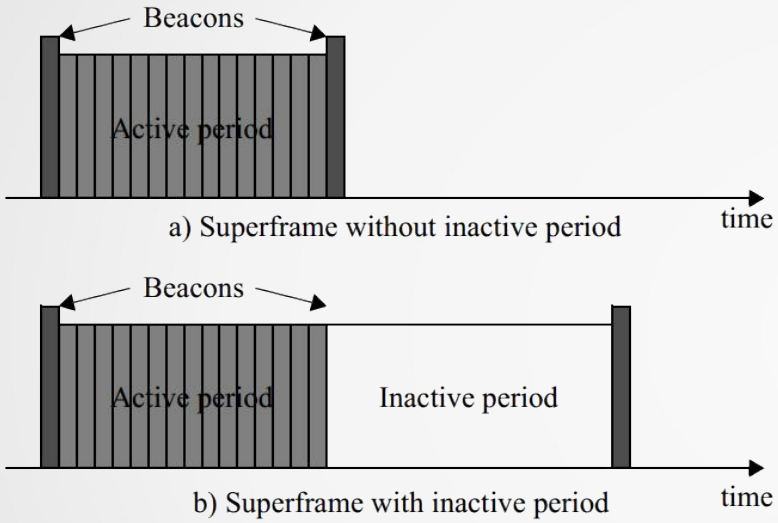


Figure 5-5—Superframe structure

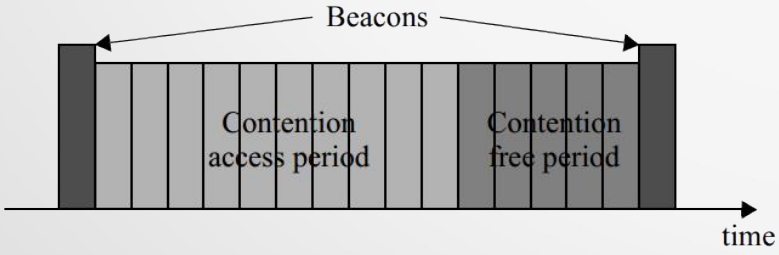


Figure 5-6—Structure of the active periods with GTSs

- DSME multi-superframe

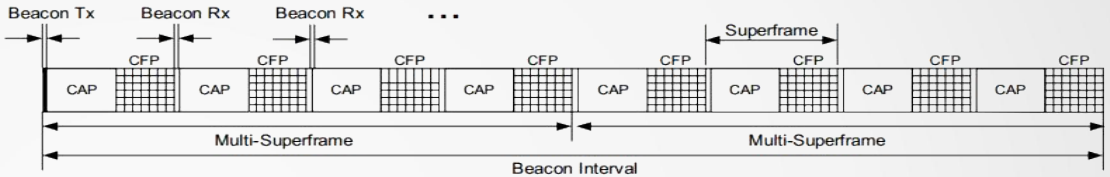


Figure 5-7—General DSME Multi-superframe Structure

- Slotframes

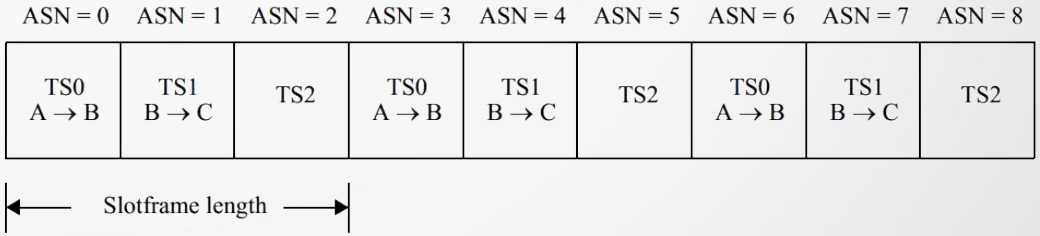


Figure 6-9—Example of a three time-slot slotframe

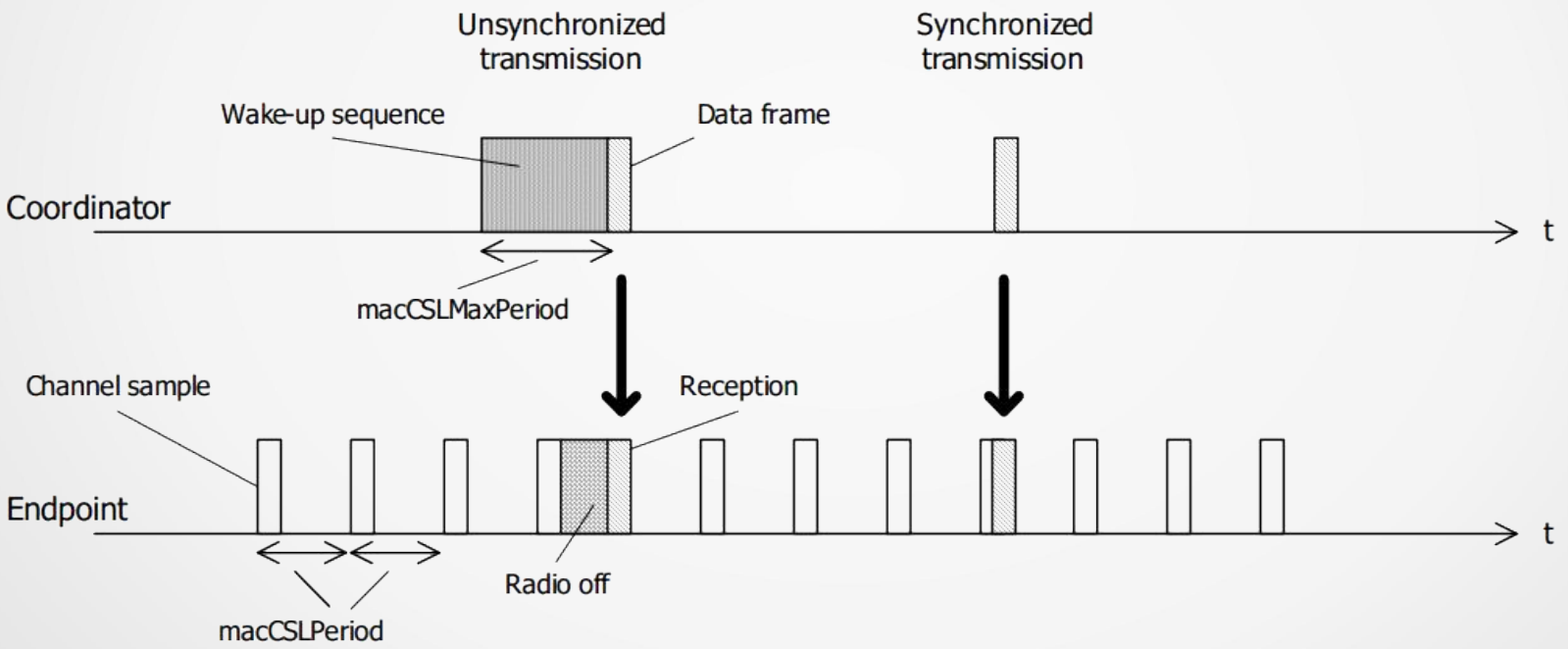
- Libre (sin beacon/superframe)

MAC: multiple access protocol

- Nonbeacon-enabled (libre): unslotted CSMA-CA
- Becon-enable: slotted CSMA-CA
- TSCH (slotframe)
  - TSCH CCA: non-shared slots
  - TSCH CSMA-CA: shared slots
  - otros

IEEE 802.15.4: CSL

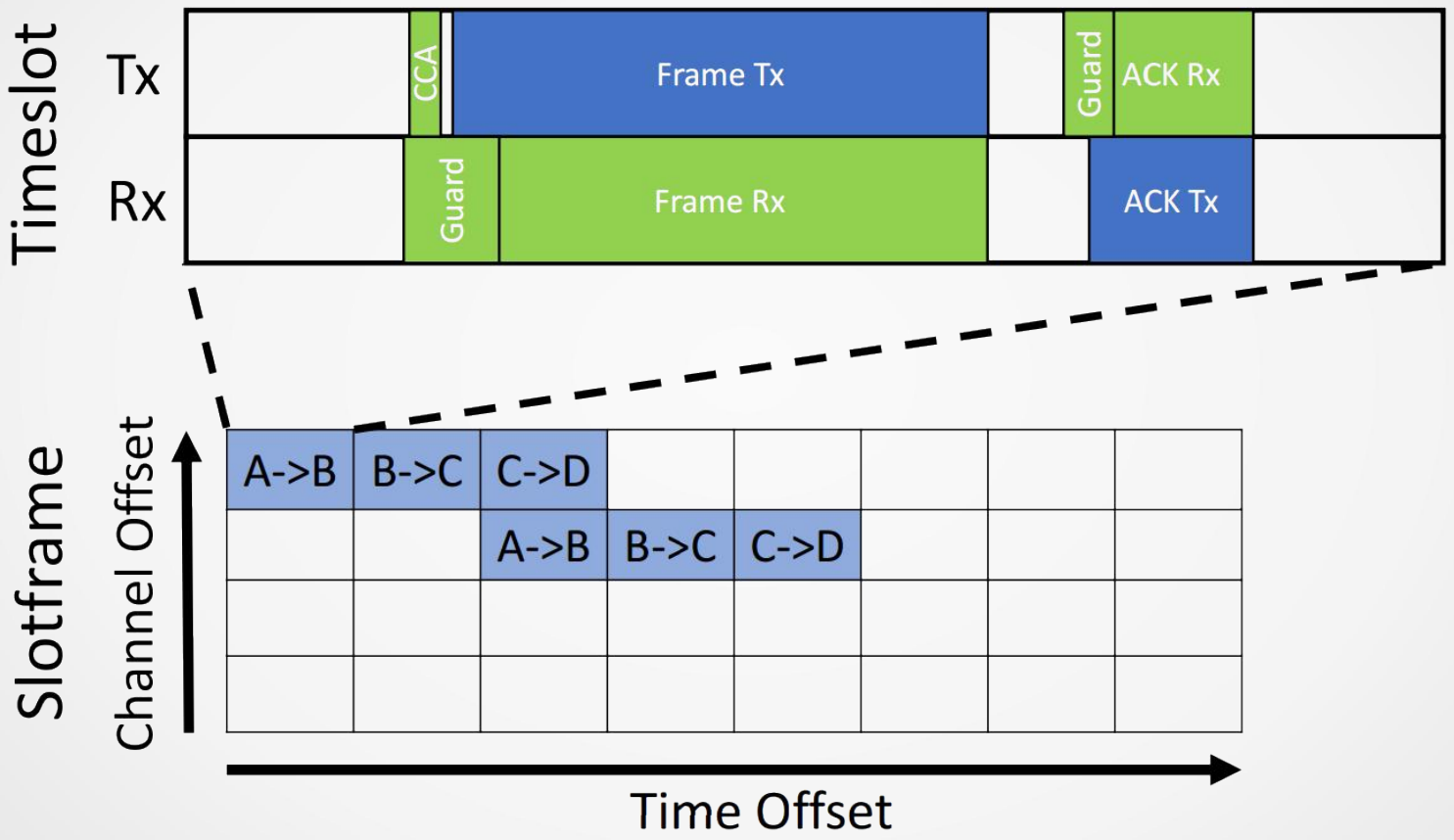
- CSL: Coordinated Sampled Listing



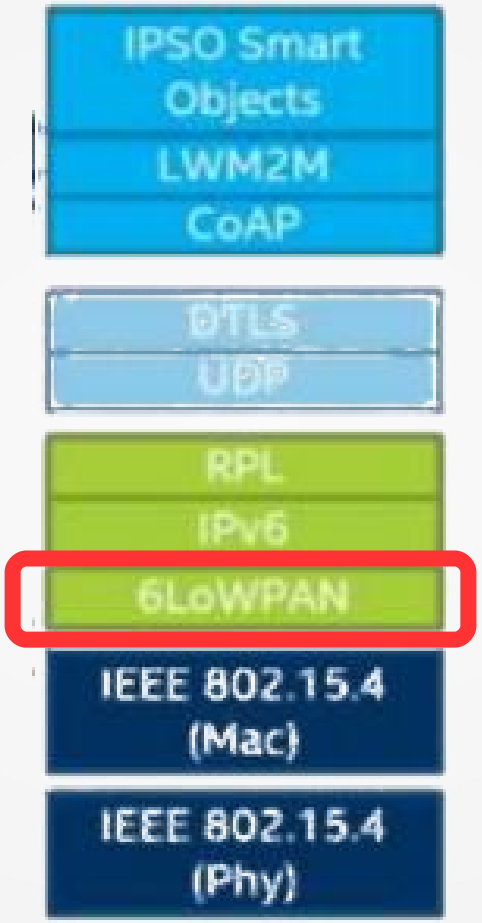
IEEE 802.15.4: TSCH

- TSCH: Time-Slotted Channel Hopping
  - **TS** (Time-Slotted): synchronization
  - **CH** (Channel Hopping):
- Objectives and benefits
  - low power consumption (keep the radio off)
  - Increasing reliability (channel diversity)
- Come from industrial protocols:
  - WirelesHART / ISA100.11

IEEE 802.15.4: TSCH



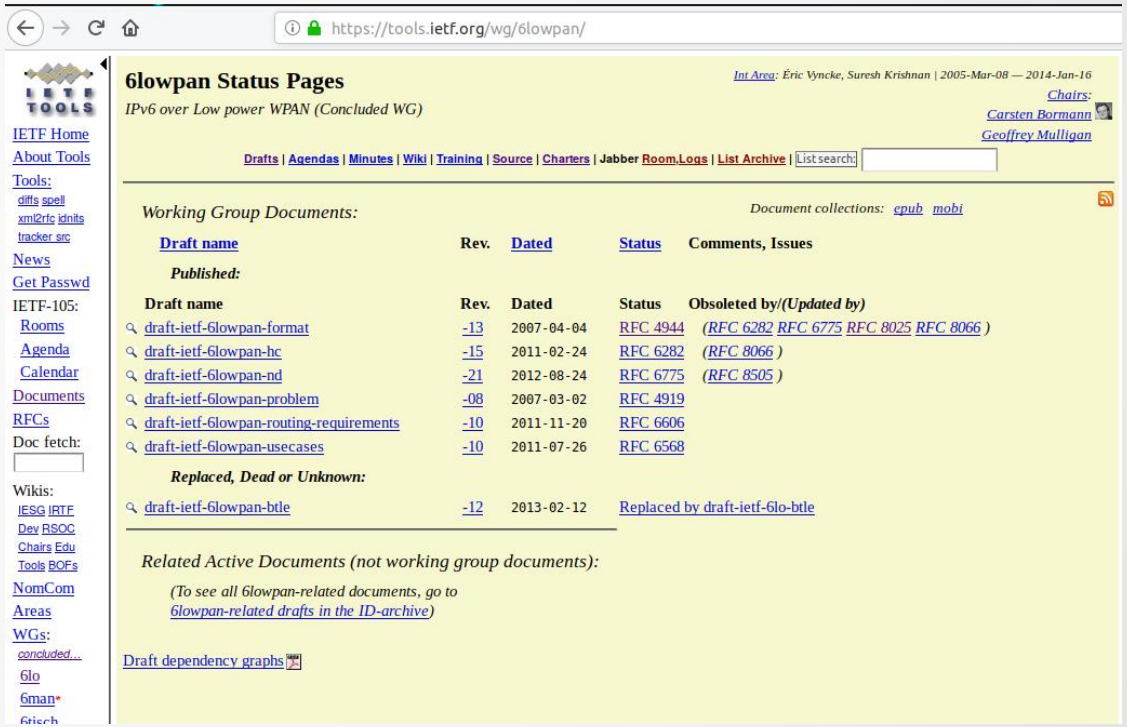
6lowpan: adaptation layer



IPv6 over Low power WPAN

- **6lowpan**: IETF Working Group (concluded)

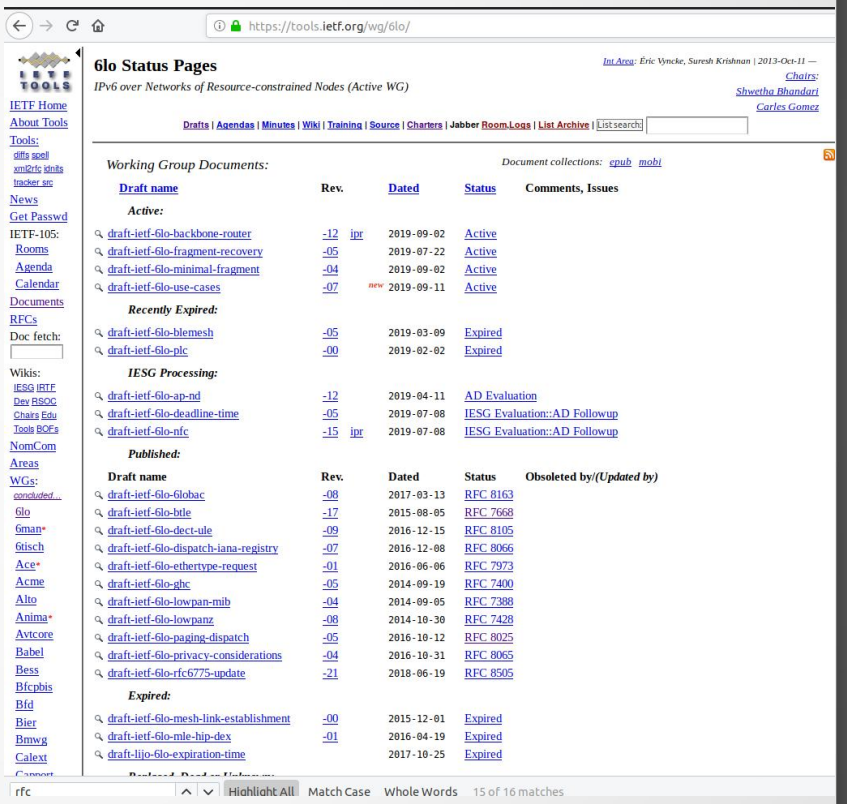
- IPv6 Packets over IEEE 802.15.4
  - RFC 4944: basis
  - RFC 6282: NHC
  - RFC 6775: ND



IPv6 over Netw. of Resource-constrained Nodes

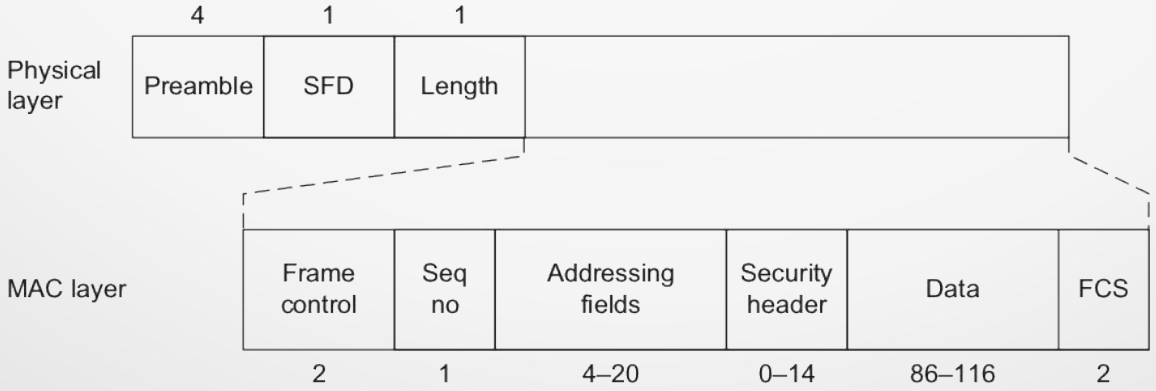
- **6lo**: IETF Working Group (active)
  - extends **6lowpan**

- IPv6-over-foo adaptation layer specifications
  - RFC 8163: MS/TP Networks (RS-485)
  - RFC 7668: Bluetooth Low Energy
  - RFC 8105: DECT – ULE
  - RFC 7428: ITU-T G.9959 Networks



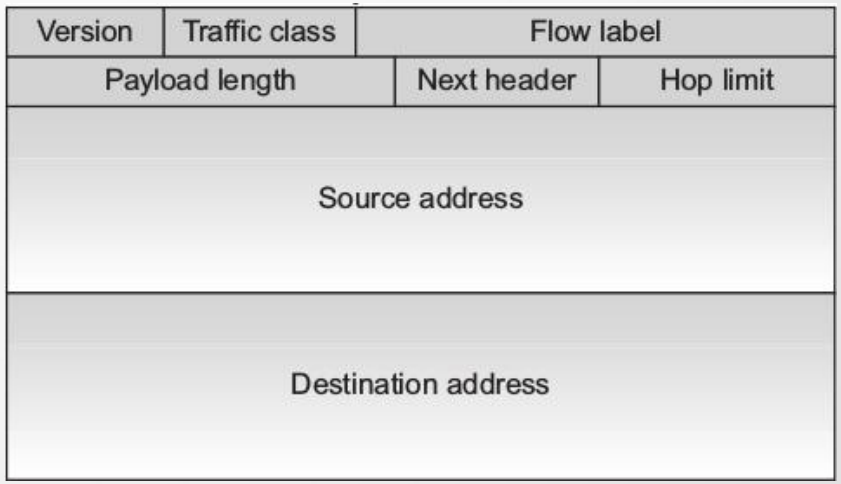
IEEE 802.15.4: some features

- Small frame: 127 bytes
  - PER reasonably low for non-negligible BER
- Addressing
  - 16-bit short / IEEE 64-bit extended MAC.
- Low data rates
  - From 50 kbps (915 MHz) to 250 kbps (2.45 GHz).



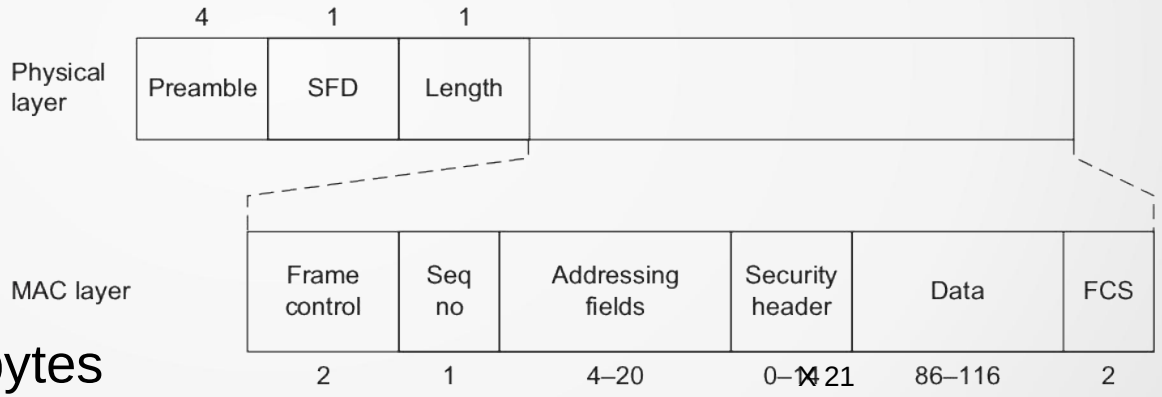
IPv6: some features

- Relatively large package: 1280 bytes.
- Addressing: 128 bits.
- Stateless address autoconfiguration (SAA)
  - Simplify configuration and management
- IPv6 includes multicast as an integral part of its architecture,
  - Neighbor Discovery (ND) uses link-local multicast for
    - address resolution
    - duplicate address detection
    - router discovery.



IPv6 over LoWPAN: challanges

- Packets IPv6 over LoWPANs.
  - Low throughput
  - Limited buffers
  - **Frames ~10 times smaller than MTU minimum MTU required by IPv6**
- Need
  - Fragmentation
  - Compression
- Example:
  - Payload effective 81 bytes
  - IPv6 header: 40 bytes
  - UDP/TCP header: 8 / 20 bytes,
  - Remains: ....

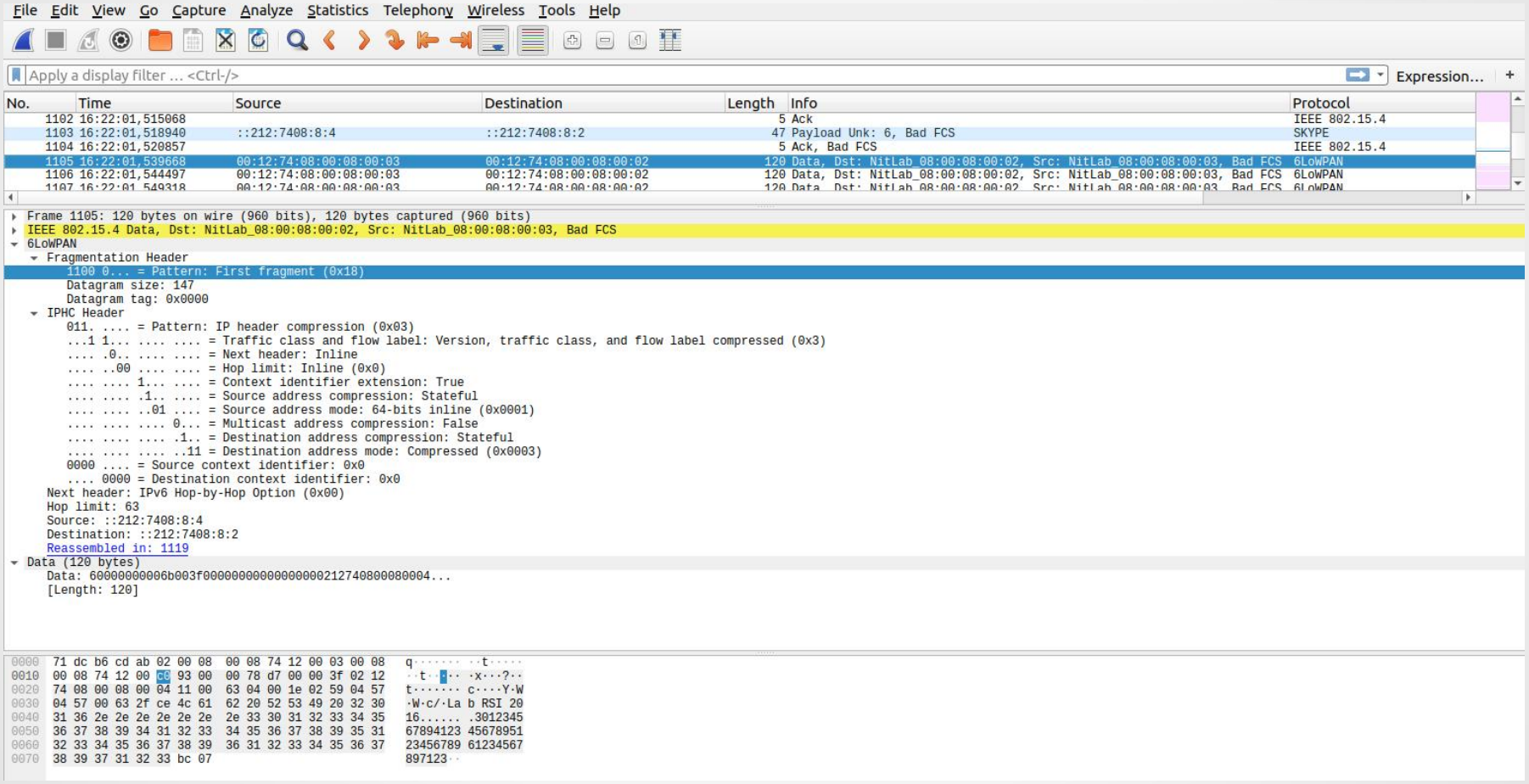


127−(2+1+20+2) = 102 bytes
AES-CCM-128: 21 extra bytes

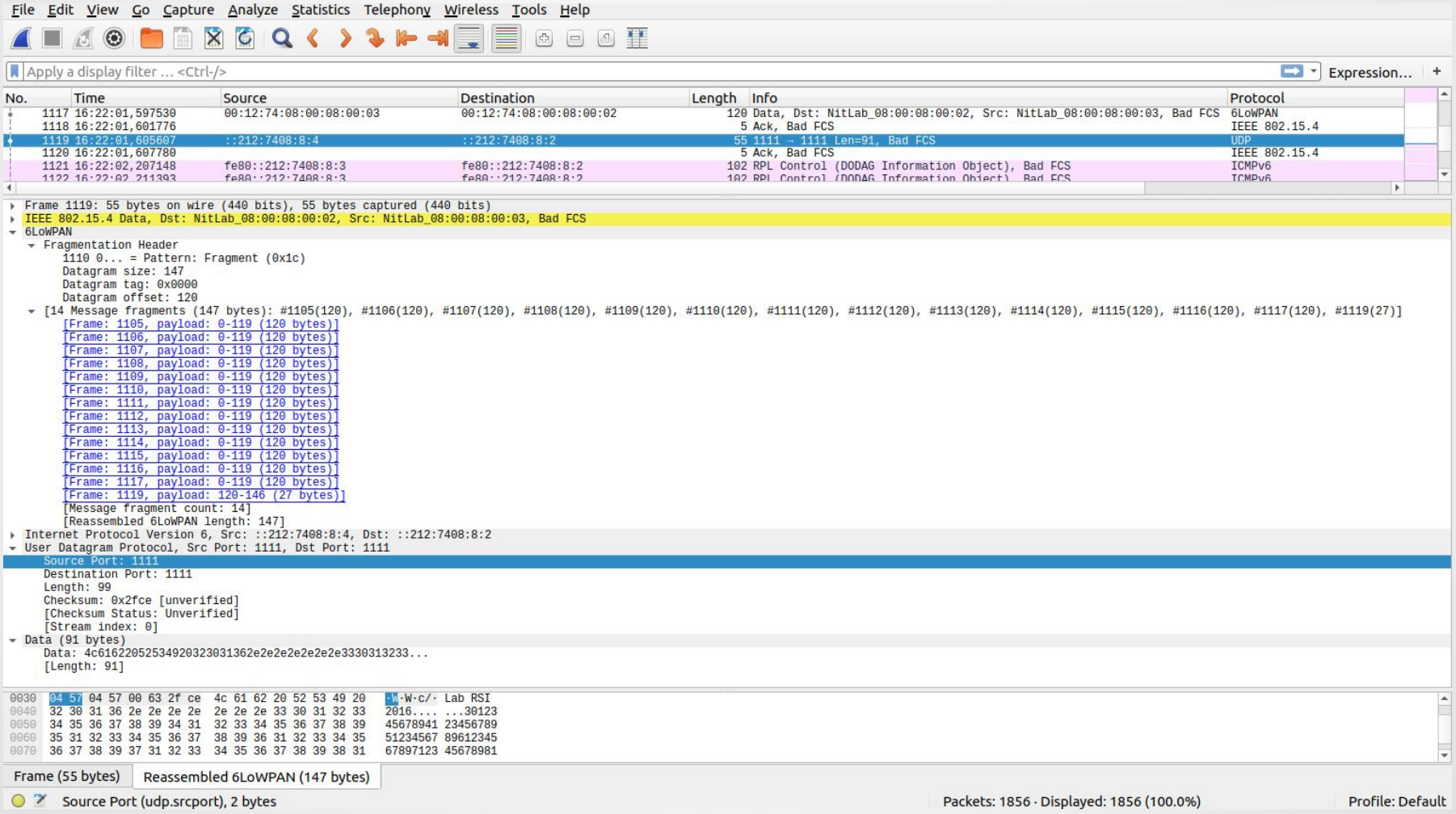
6LoWPAN: services & design

- Services:
  - Fragmented and reassembled packages
  - Header Compression
  - Layer 2 routing “mesh-under”
- IEEE 802.15.4 encapsulates IPv6 packet
  - “encapsulation header stack” before each IPv6 packet
  - dispach byte (primer byte): identify the next header
  - Three headers:
    - mesh addressing header
    - fragment header
    - IPv6 header compression header

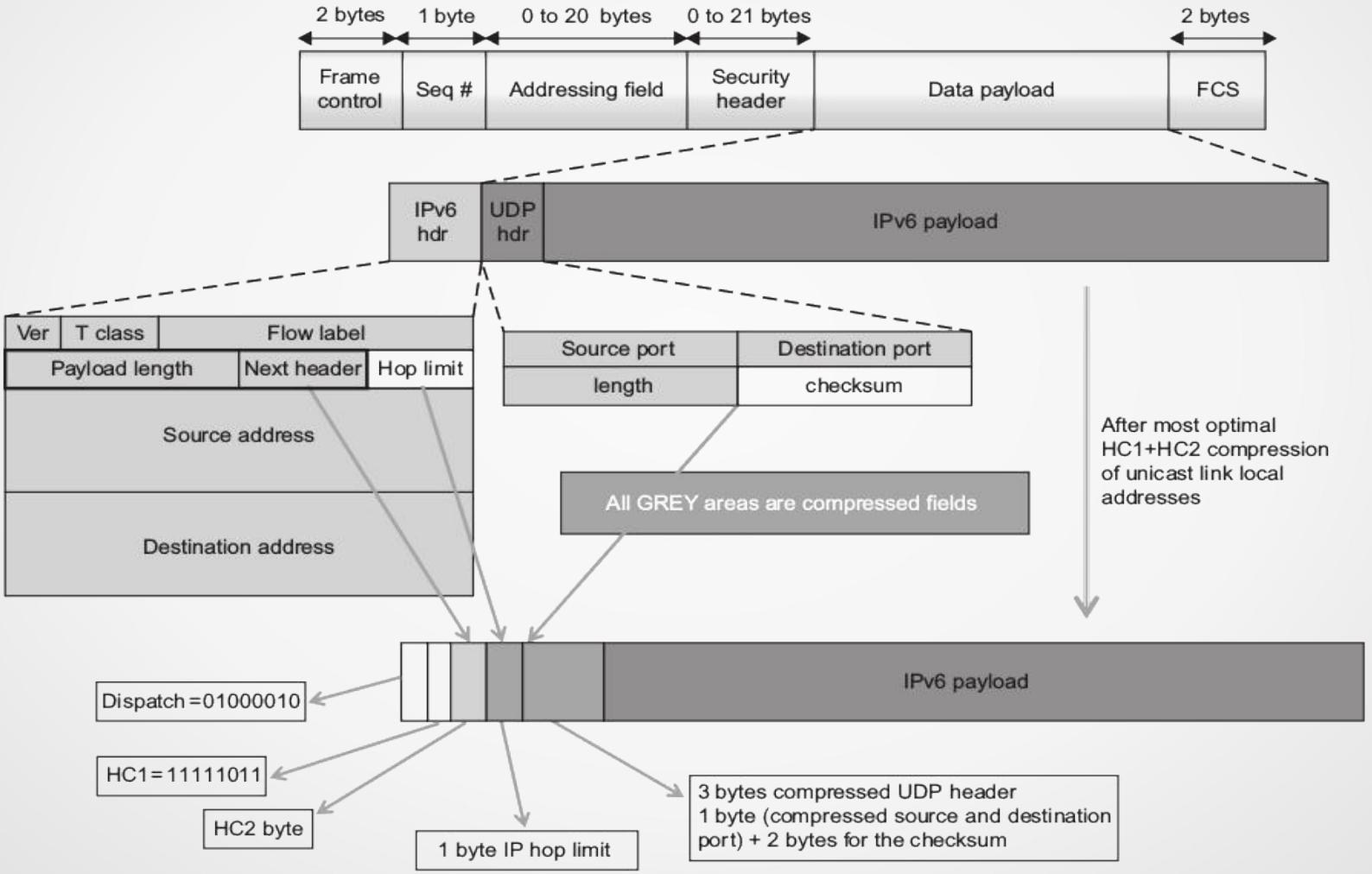
6lowpan: wireshark



6lowpan: wireshark



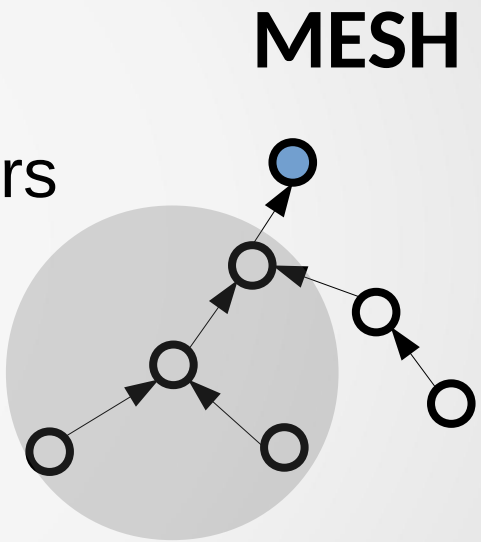
6lowpan: example



RPL: routing layer

RPL

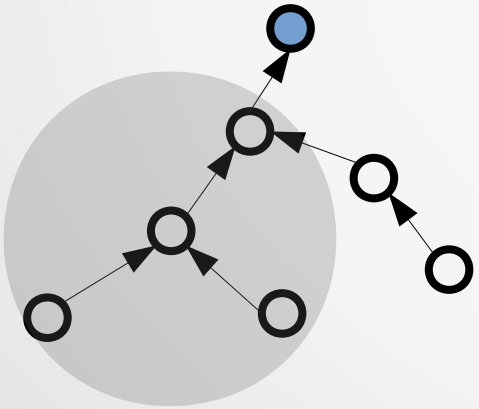
- IPv6 **R**outing **P**rotocol for **L**ow-Power and Lossy Networks (RPL, pronounced ripple)
- Features
  - Physical medium: IEEE 802.15.4 or others
  - Proactive: distance vector based
  - Topology: tree (build graph distributed)
  - Traffic: "up" and "down" directions
  - Parent selection: based on objective function
  - Operation mode: non-storing and storing



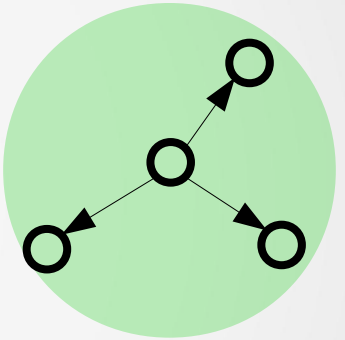
RPL

- Requires:
  - broadcast and unicast messages to build tree

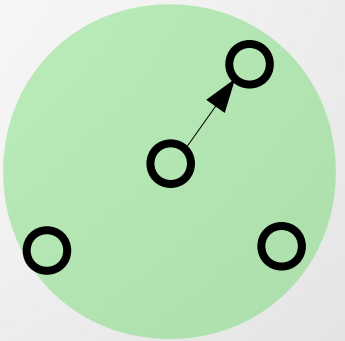
MESH



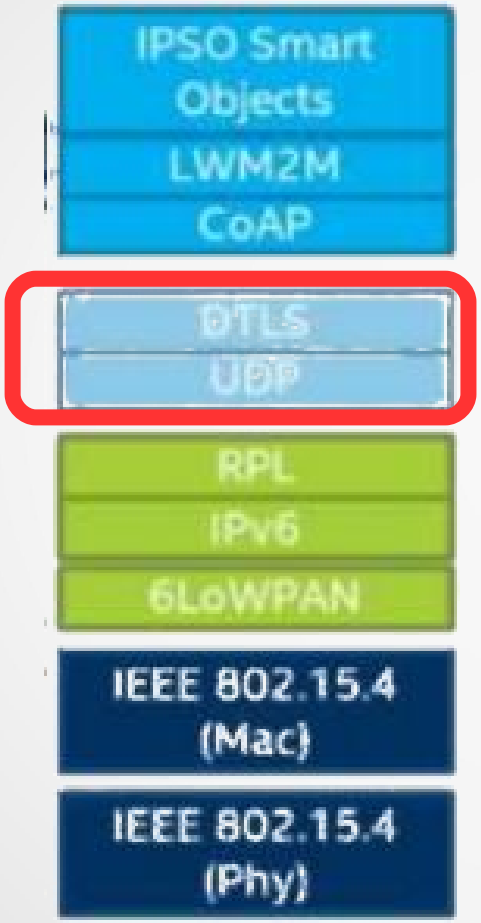
broadcast



unicast

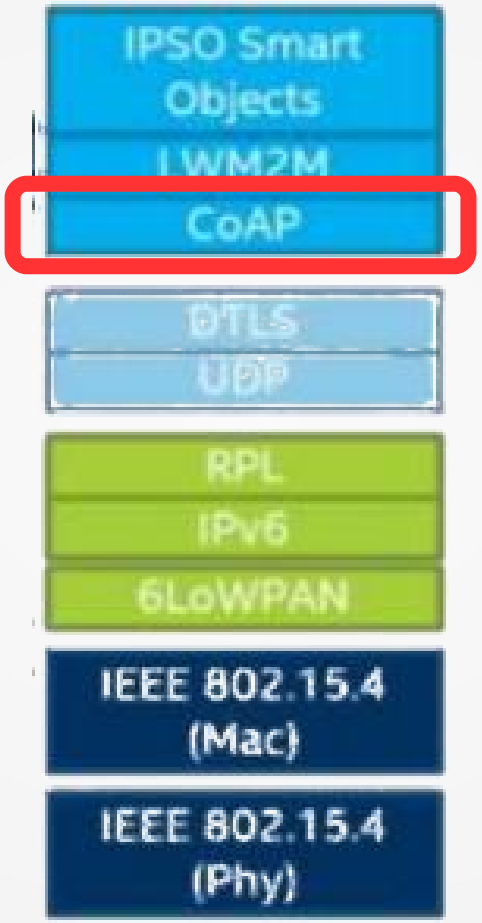


TCP / UDP: transport layer



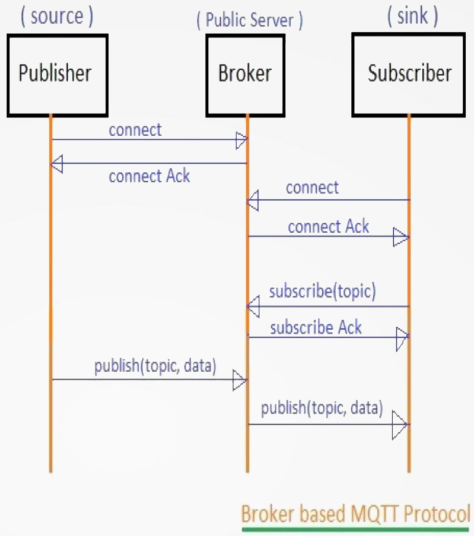
- TCP versus UDP

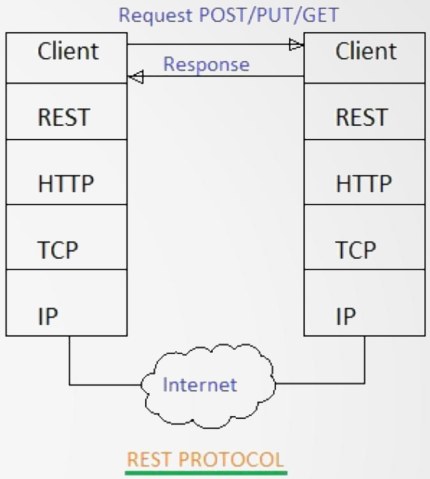
CoAP: application layer



Application protocols: options

- Proprietary solutions
  - disadvantages
- Existing solutions
  - Client - Server
  - Publish - Subscribe



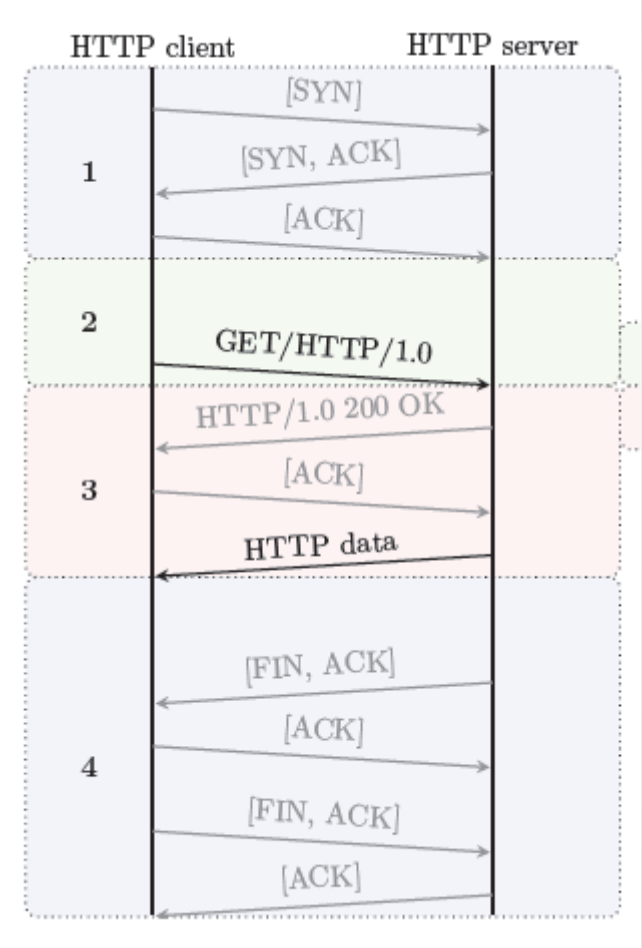


- Example: Extend the use of web services (client server)
  - Hypertext Transfer Protocol (HTTP)
  - New protocols

Example: HTTP

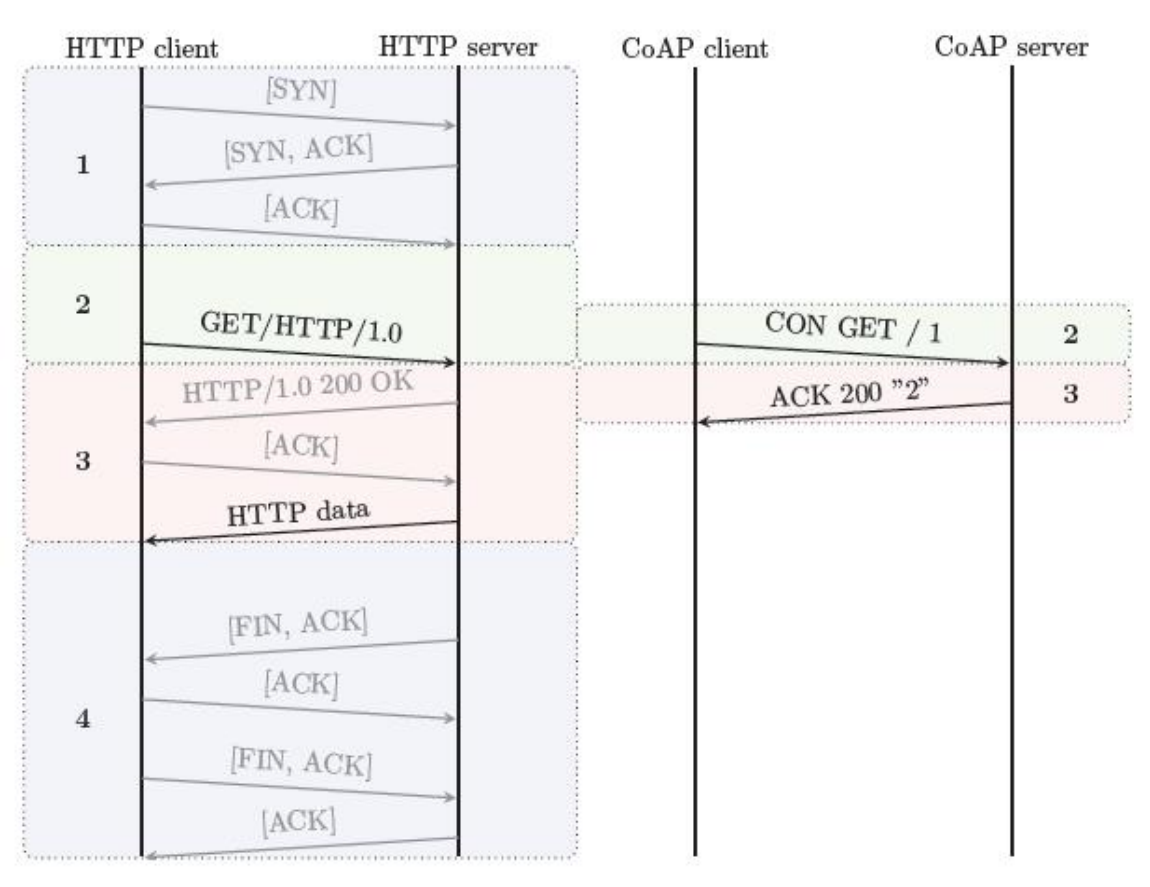
- Features
  - Restful
  - TCP

- Is it a good idea for WSN?
  - No



CoAP: new proposal

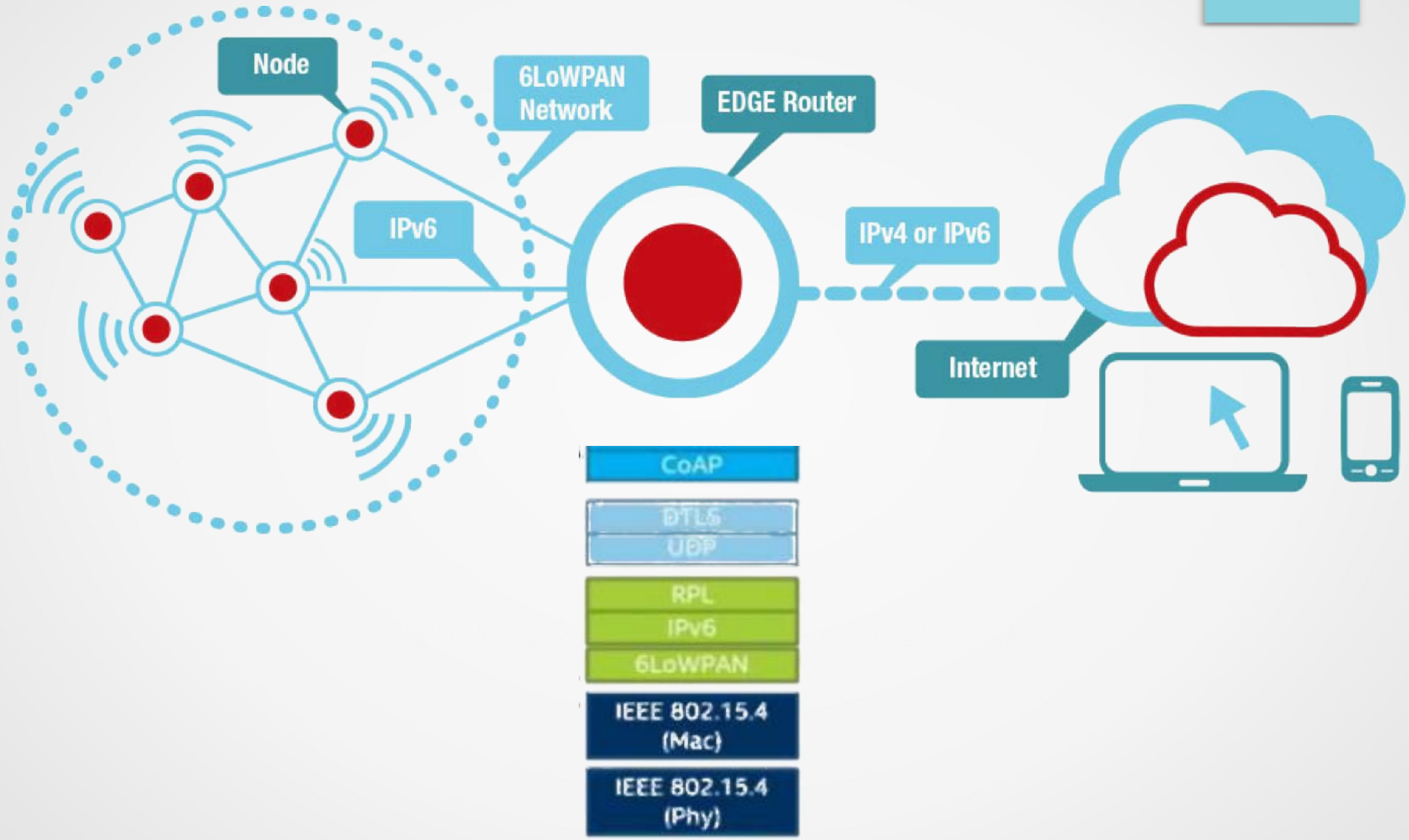
- RFC 7252: The Constrained Application Protocol (CoAP)
- RESTful
  - fresh start
- Transport: UDP (optionally DTLS)



CoAP: two layers

- Methods
  - GET
  - PUT
  - POST
  - DELETE
- Messages
  - Confirmable
  - Non-confirmable
  - Acknowledgment
  - Reset

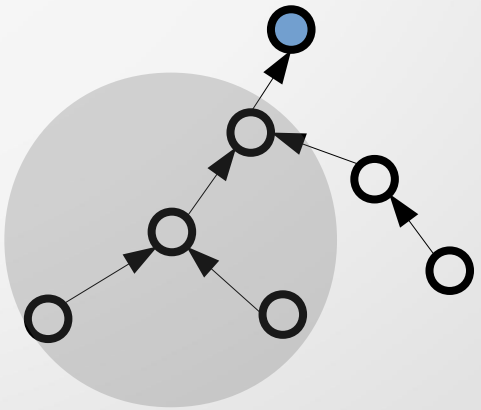
Recap


Node
6LoWPAN Network
EDGE Router
IPv6
IPv4 or IPv6
Internet
CoAP
DTLS
UDP
RPL
IPv6
6LoWPAN
IEEE 802.15.4 (Mac)
IEEE 802.15.4 (Phy)

WSN (mesh) and Cyber Physical Systems

- Some potential benefits
  - 2.4 GHz and sub-GHz bands available
  - homogeneous devices and communications (allows)
  - relative high throughput (compared to other LPWAN)
  - traffic upwards and downwards (do not prioritize upwards)
  - enable peer to peer communications

MESH



thanks
¿questions?