

# **Advanced Internet and IoT Technologies**

## **- Introduction to the Internet of Things -**

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# Agenda

🕒 The Internet of Things

➡ Motivation and Use Cases

🕒 IoT on Wireless Link Layers

🕒 IP in the Internet of Things

# What is the Internet of Things?

*A system in which objects in the physical world can be connected to the Internet by sensors and actuators (coined 1999 by Kevin Ashton)*

Key aspects:

- E2E communication via Internet standards
- Machine-to-machine communication
- Embedded devices, often constrained and on battery
- Typically without user interface
- Very large multiplicities, w/o manual maintenance

# IoT: Connecting the Physical World to the Internet



# IoT: Connecting the Physical World to the Internet

Industrial  
Automation



Connected Vehicles

# IoT: Connecting the Physical World to the Internet



# Industrial Automation



## Connected Vehicles



# Smart Homes

# IoT: Connecting the Physical World to the Internet



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## Connected Vehicles



# Smart Homes



# eHealth



# IoT: Connecting the Physical World to the Internet



Micro- & Nano Satellites



Connected Vehicles



Smart Homes

Industrial  
Automation



eHealth

# Use Case: Security in Harsh Industrial Environments



# Use Case: Security in Harsh Industrial Environments



# Use Case: Security in Harsh Industrial Environments

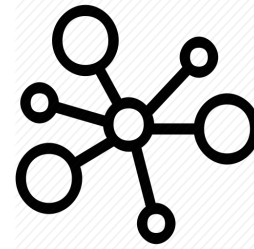
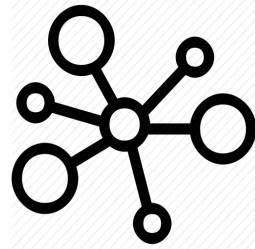




# Use Case: Security in Harsh Industrial Environments



# Use Case: Security in Harsh Industrial Environments





# Smart DOM Hamburg



# „Smart‘ Heating





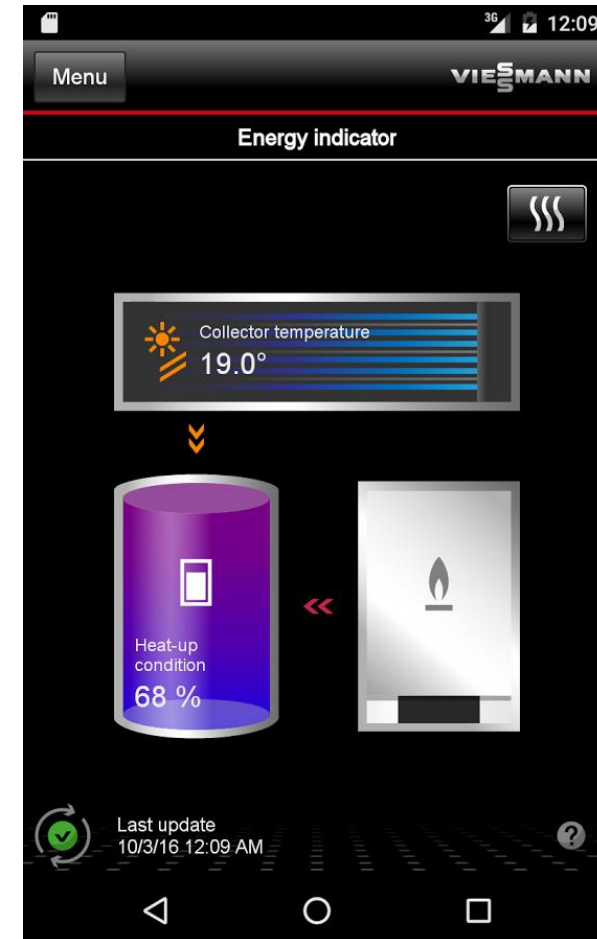
# „Smart“ Heating



# „Smart‘ Heating



# „Smart‘ Heating



# Evolution Towards an IoT

**Embedded  
Controllers**

**Wireless  
Networking**

**IPv4 Uplink  
to the Cloud**

# Evolution Towards an IoT

Distributed local  
intelligence

Embedded  
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IPv4 Uplink  
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# Evolution Towards an IoT

Distributed local  
intelligence

Embedded  
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+

Wireless sensor  
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Wireless  
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IPv4 Uplink  
to the Cloud

# Evolution Towards an IoT

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Wireless sensor  
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Wireless  
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Internet of  
Things ?

IPv4 Uplink  
to the Cloud

This is not yet an  
**Internet**  
of Things!

# No Internet without Open Speech and Open Standards



**I E T F<sup>®</sup>**



|             |                                                                                 |
|-------------|---------------------------------------------------------------------------------|
| Application | XHTML<br>XDI      CBOR      RDF<br>JSON      Telnet<br>CoAP      HTTP      XMPP |
| Transport   | TCP      UDP      TLS/SSL                                                       |
| Network     | OSPF      RPL      DHCP      BGP<br>OLSR IPv6      SLAAC      IPv4              |
| Link        | IEEE802.15.4      LoRa      BLE<br>Ethernet                                     |

# Evolution towards an *Internet oT*

Distributed local  
intelligence

Embedded  
Controllers

+

Wireless sensor  
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Wireless  
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+

Hype-Internet  
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IPv4 Uplink  
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# Evolution towards an *Internet oT*

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Interoperable  
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# Evolution towards an *Internet oT*

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# Evolution towards an *Internet oT*

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Things loosely  
joined by IPv6

+

+

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# Evolution towards an *Internet oT*

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The Real Internet of Things (C. Bormann)

# The many faces of the IoT

## High-end IoT



Processor: GHz, 32/64 Bit  
Memory: M/Gbytes  
Energy: Watt  
Network access: 5G, WLAN

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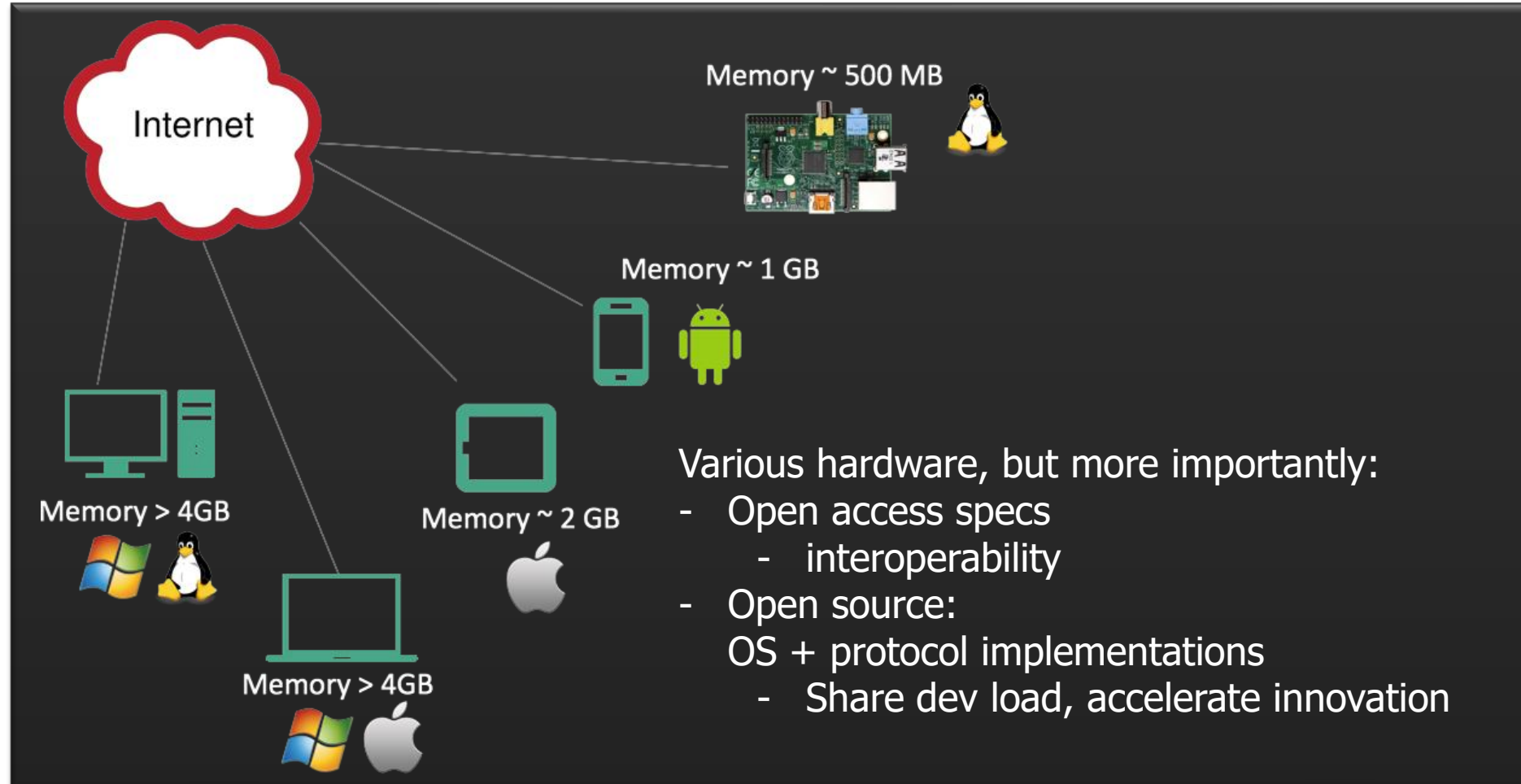
## Low-end (or constrained) IoT



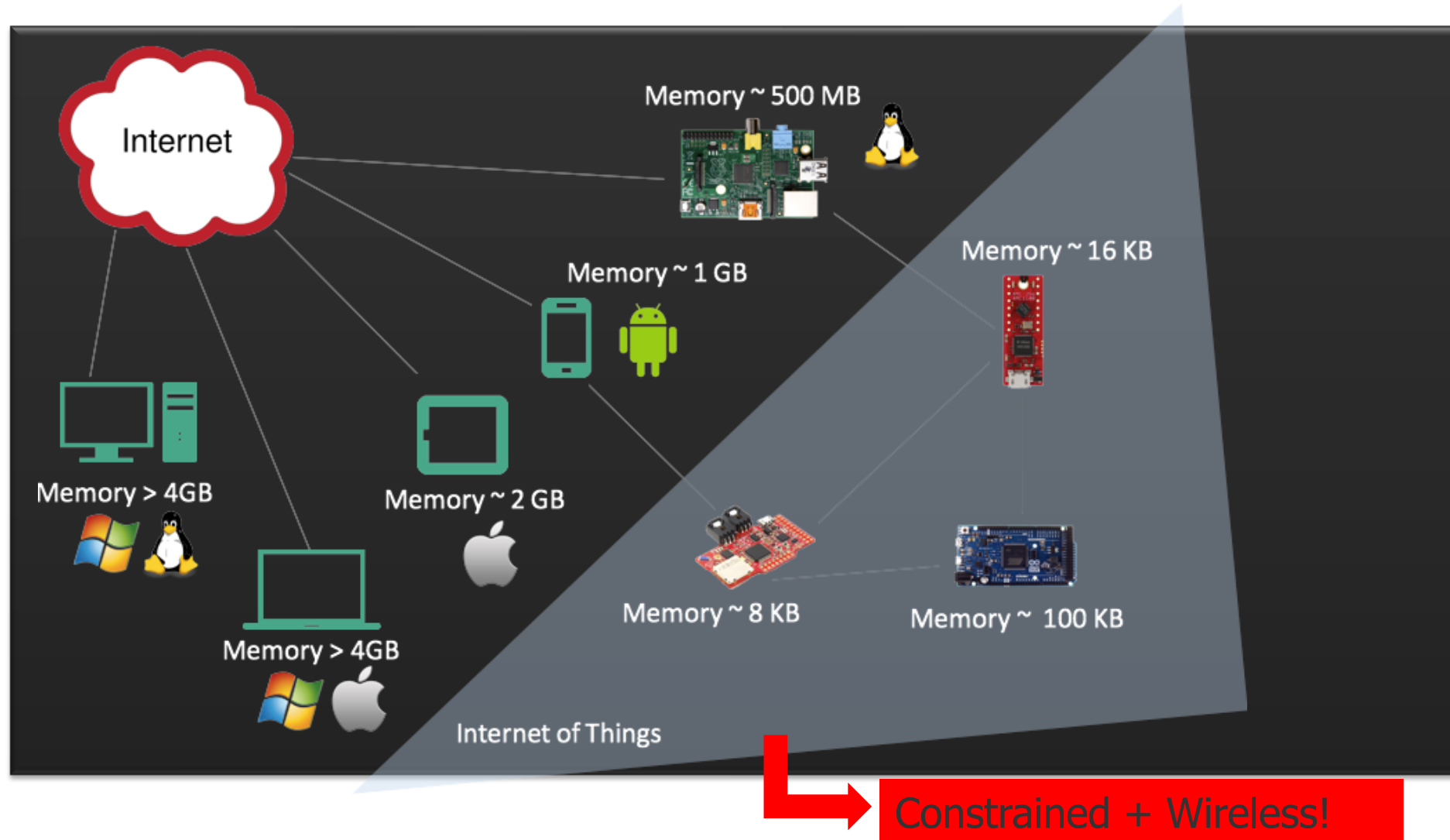
Processor: MHz, 8/16/32 Bit  
 Memory: kbytes  
 Energy: MWatt  
 Network access: 802.15.4, BLE



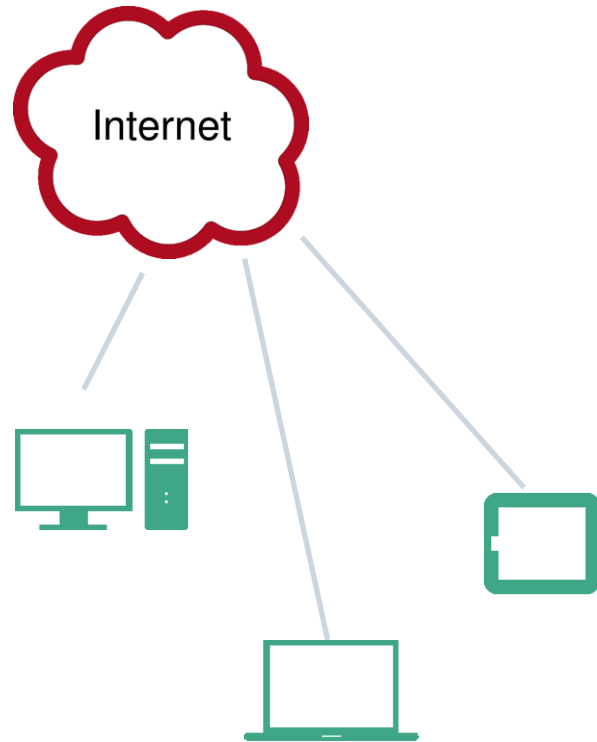
# The Internet (as we know it)



# The Internet of Things (IoT)

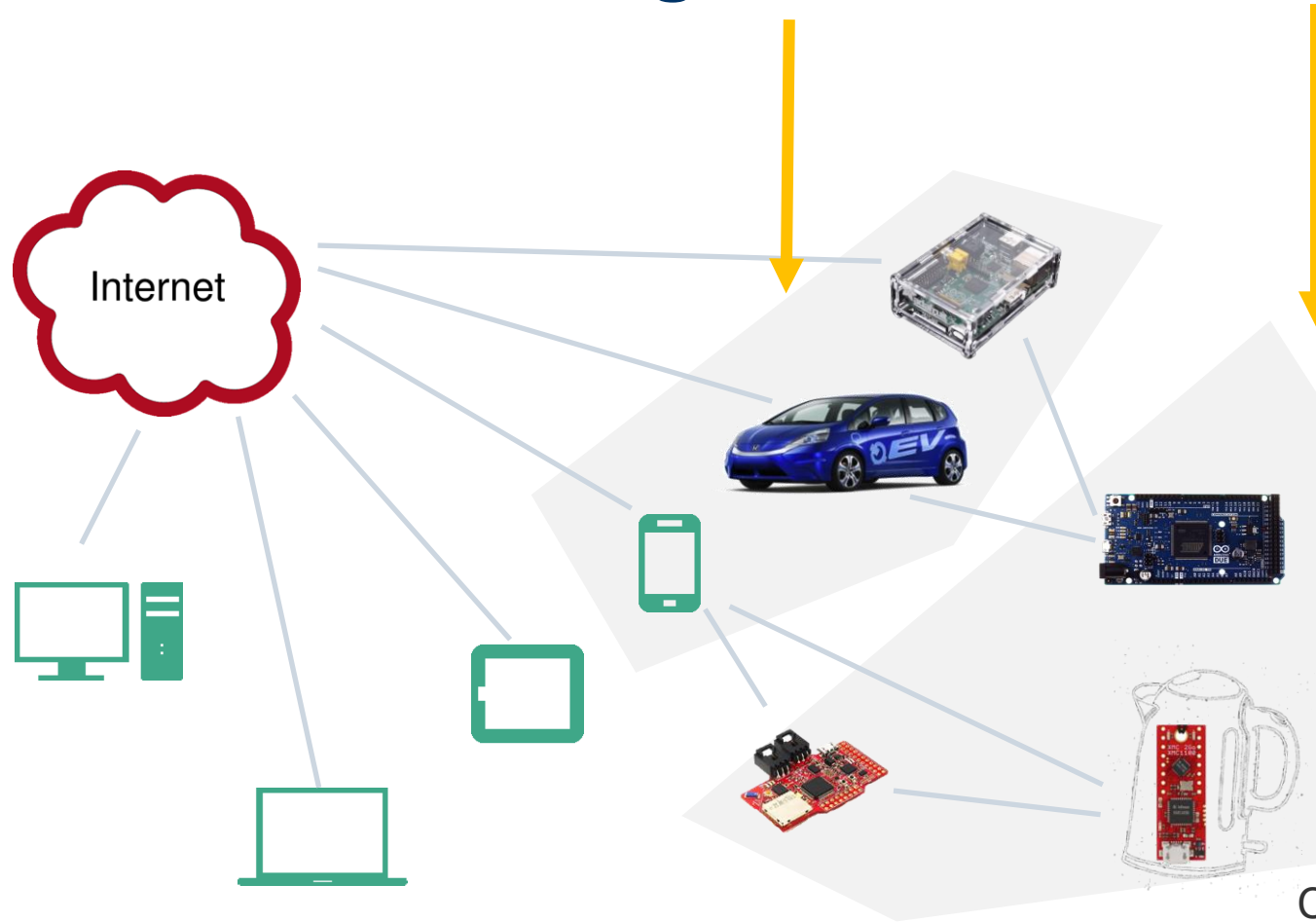


# IoT Devices:



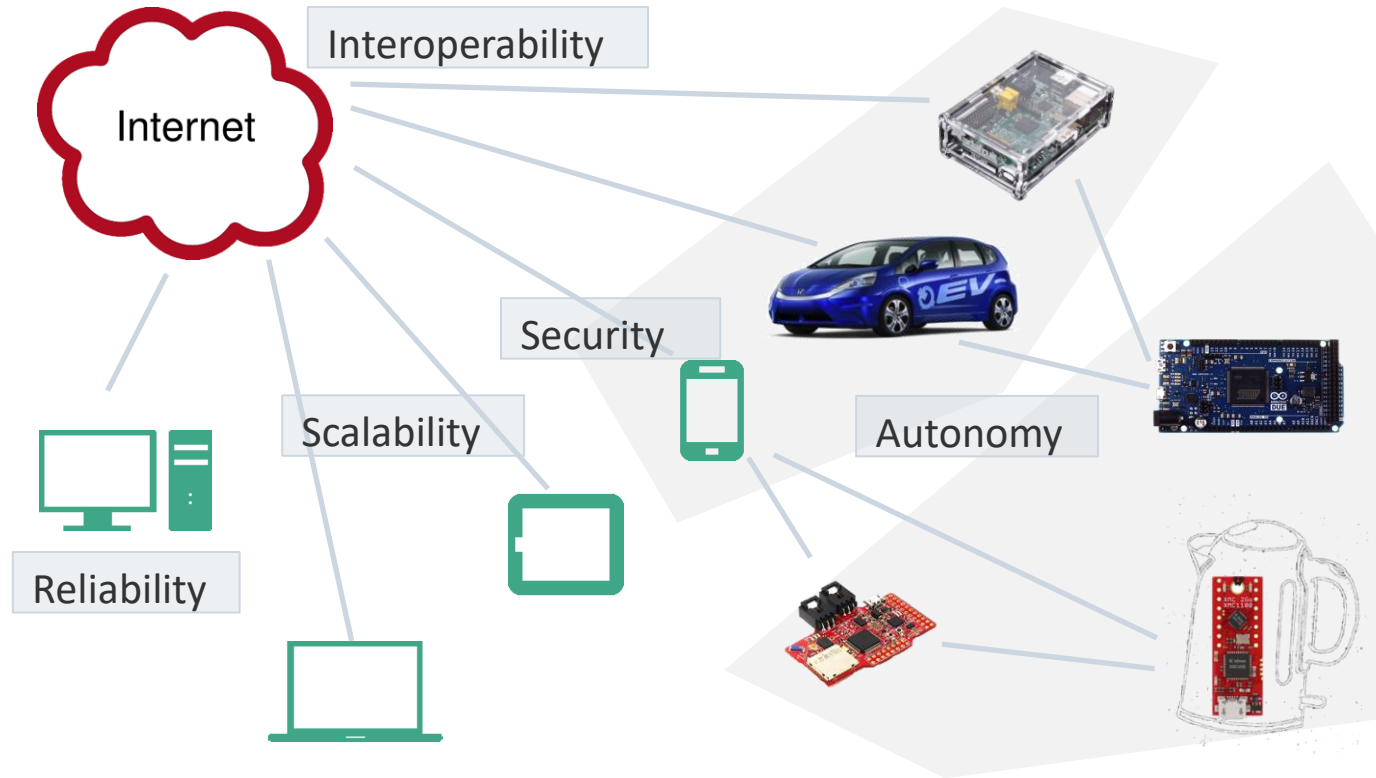
# IoT Devices:

## High-end vs Low-end

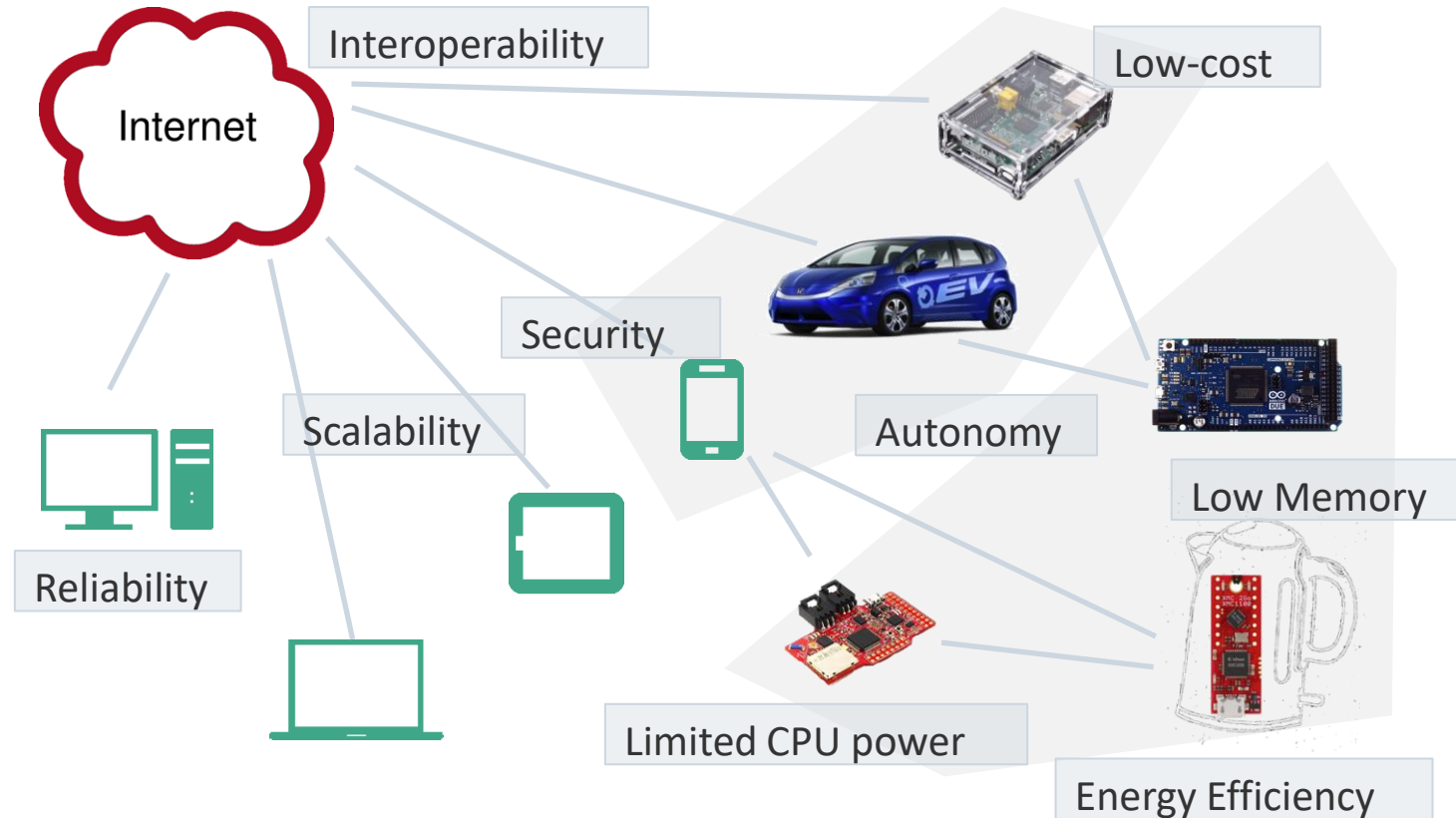


C.Bormann et al. "RFC 7228:  
Terminology for Constrained-Node  
Networks," IETF, May 2014.

# IoT Requirements



# IoT Requirements: Constraints

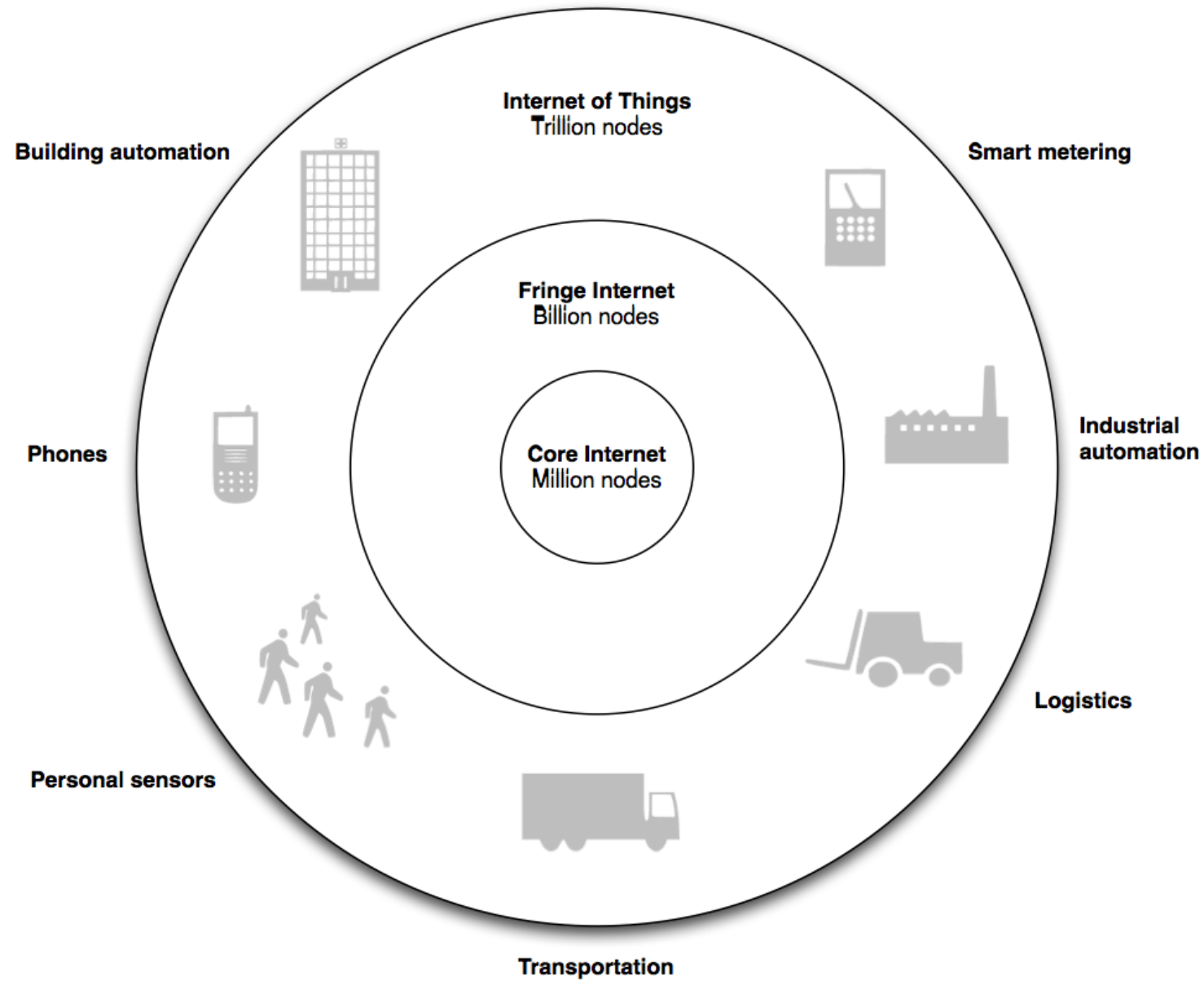


# IoT Key Challenges

Five key areas according to ISOC:

1. Security
2. Privacy
3. Interoperability and standards
4. Legal, regulatory, and rights
5. Emerging economies and development





# The IoT is Very Heterogeneous

Various boards

A zoo of components

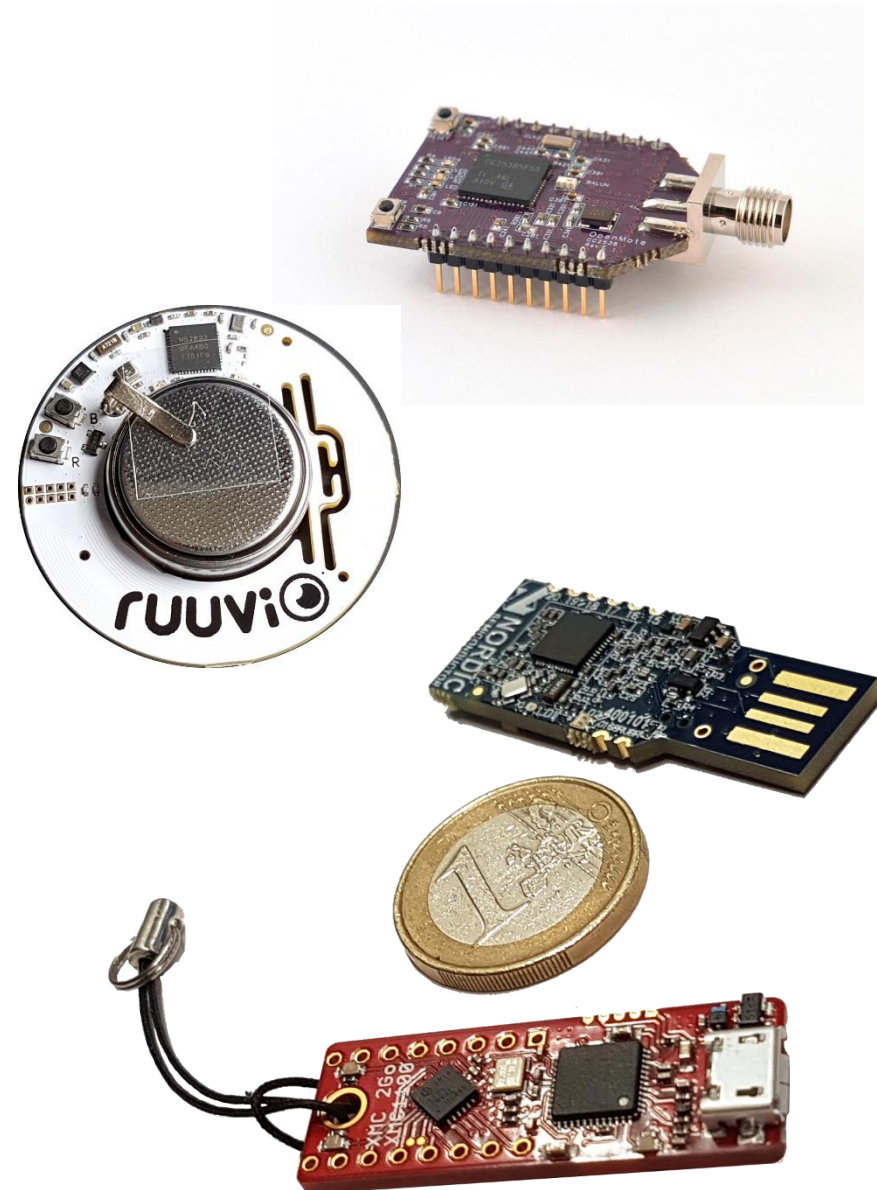
Broad range of radios

Different Link-layers

Competing network layers

Diverging interests and technologies

A lot of experimentation ...



# IoT Applications

Facility, Building and Home Automation

SmartCities & SmartGrids

Personal Sports & Entertainment

Healthcare and Wellbeing

Asset Management

Advanced Metering Infrastructures

Environmental Monitoring

Security and Safety

Industrial Automation

# IoT Use Cases



Nature Monitoring



Industry 4.0

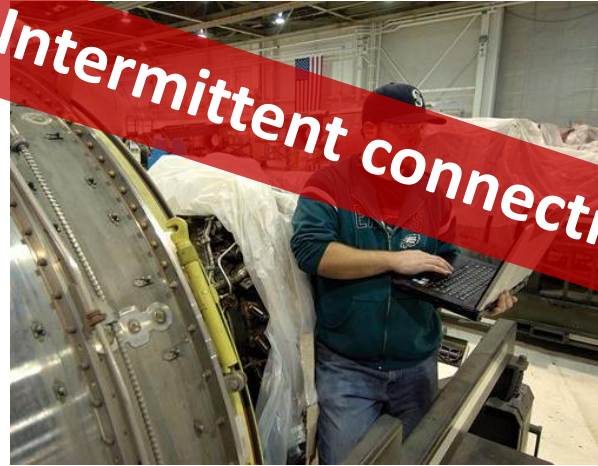


Micro Satellites

# IoT Use Cases



Nature Monitoring



Industry 4.0



Micro Satellites



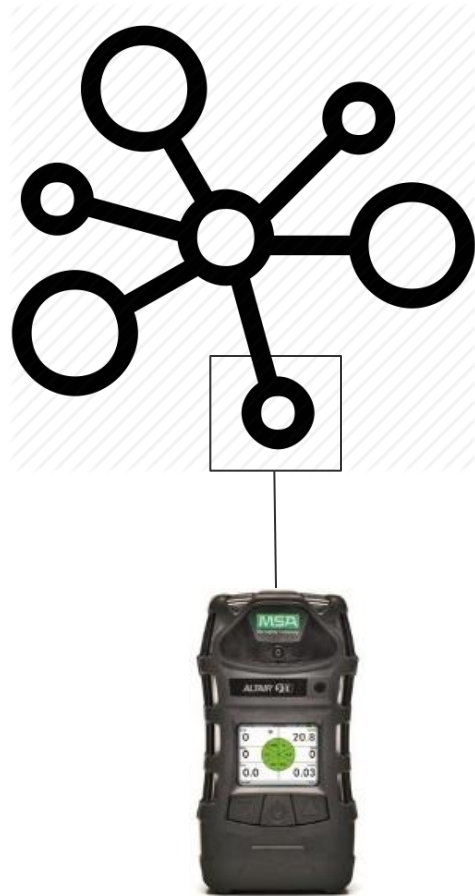
# Use Case Safety Monitoring

Workers in industrial process plants

- Perform maintenance in safety-critical environments
- Dangerous events may occur at any time
  - exposure to toxic/combustible gases
  - oxygen depletion in confined spaces
  - gas leaks/sudden outbursts of fire
- Continuous recording of sensor data required



# Technical Setting



Body sensors

- IoT controller

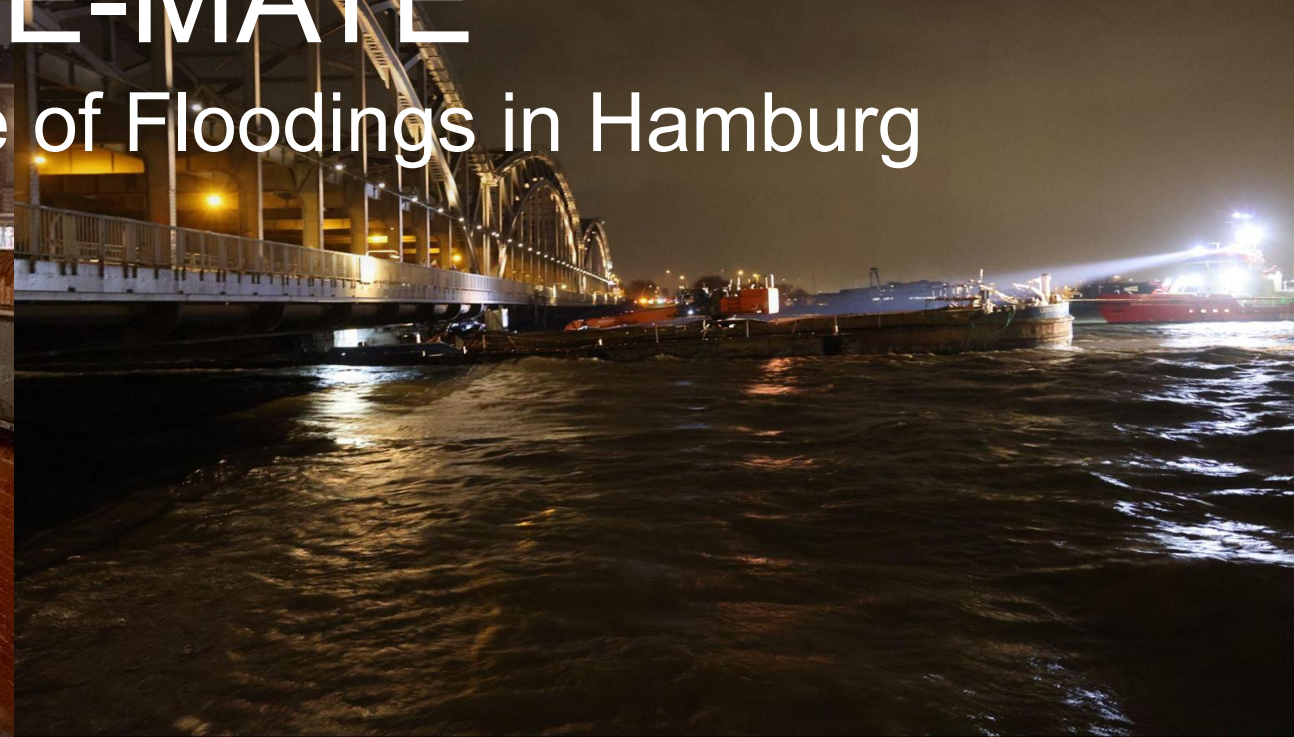
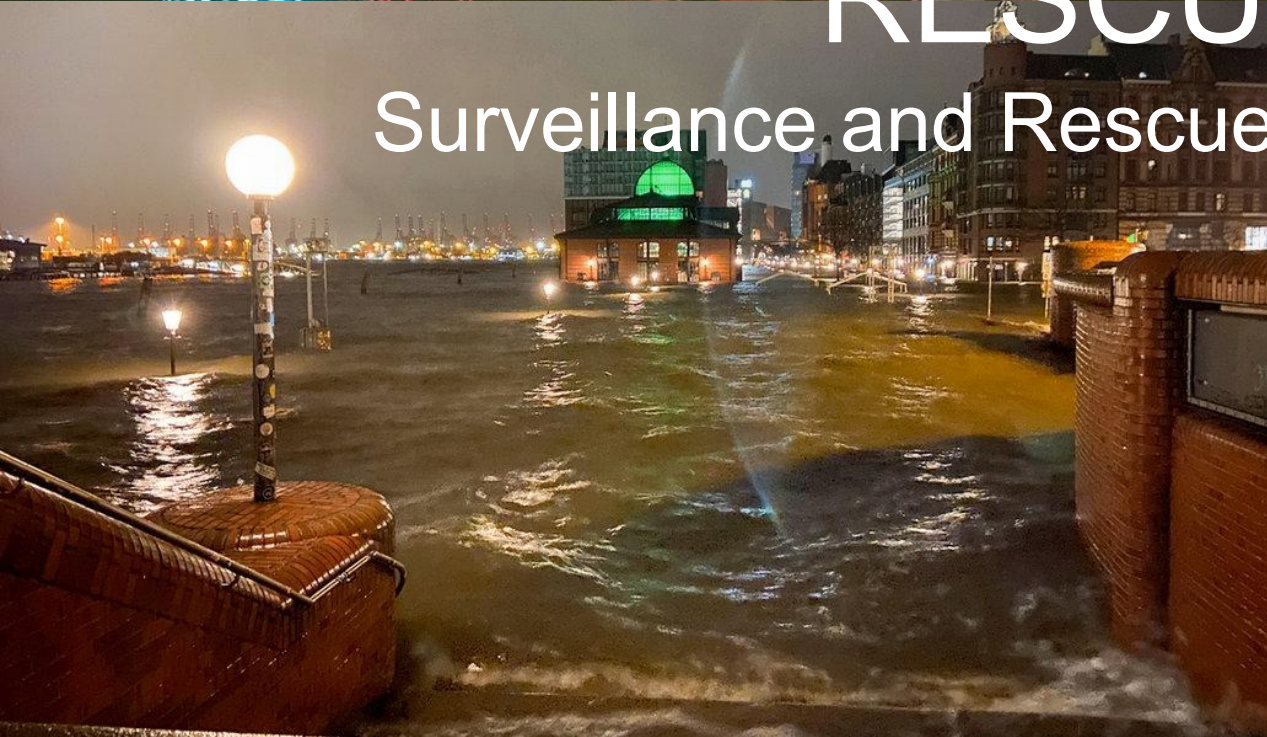
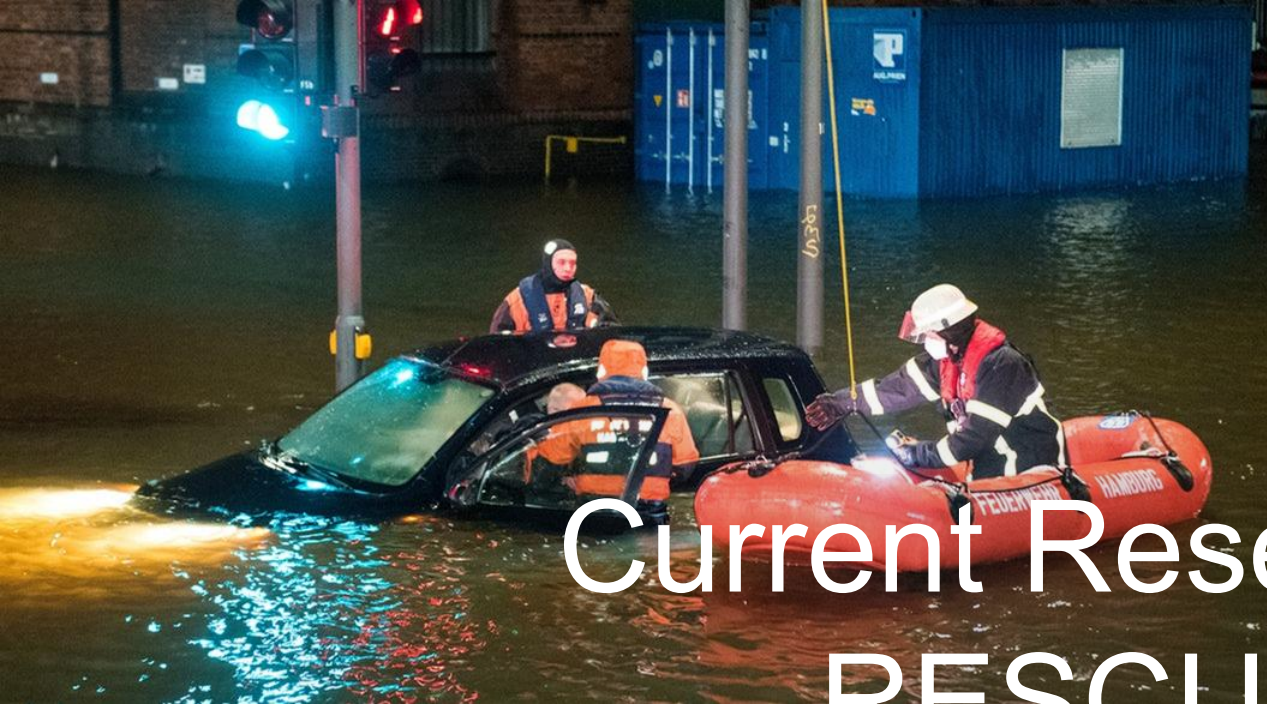
Protocols

- Alarm
- Mission log
- Configuration
- Management

Communication via border gateway to cloud

- **Mobility**
- **Intermittent connectivity**





# Current Research Project RESCUE-MATE

Surveillance and Rescue of Floodings in Hamburg



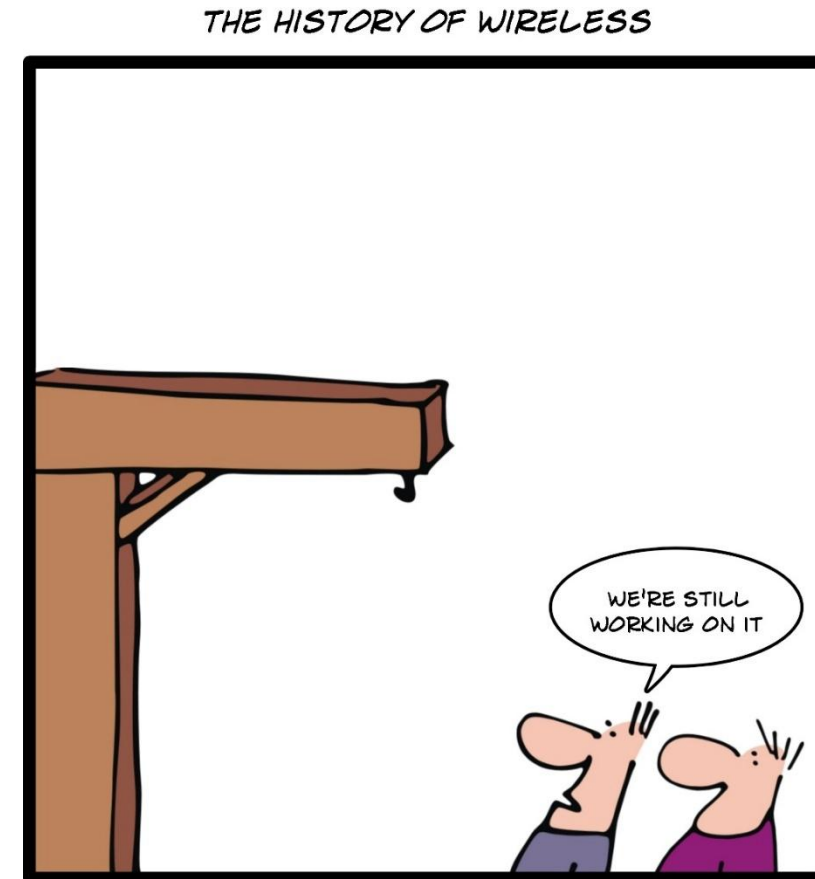
# Agenda

- 🕒 The Internet of Things
- 🕒 IoT on Wireless Link Layers
  - ➡ Excursion to the World of Wireless
  - ➡ Low Power Lossy Links
- 🕒 IP in the Internet of Things

# Mobile Wireless Networks

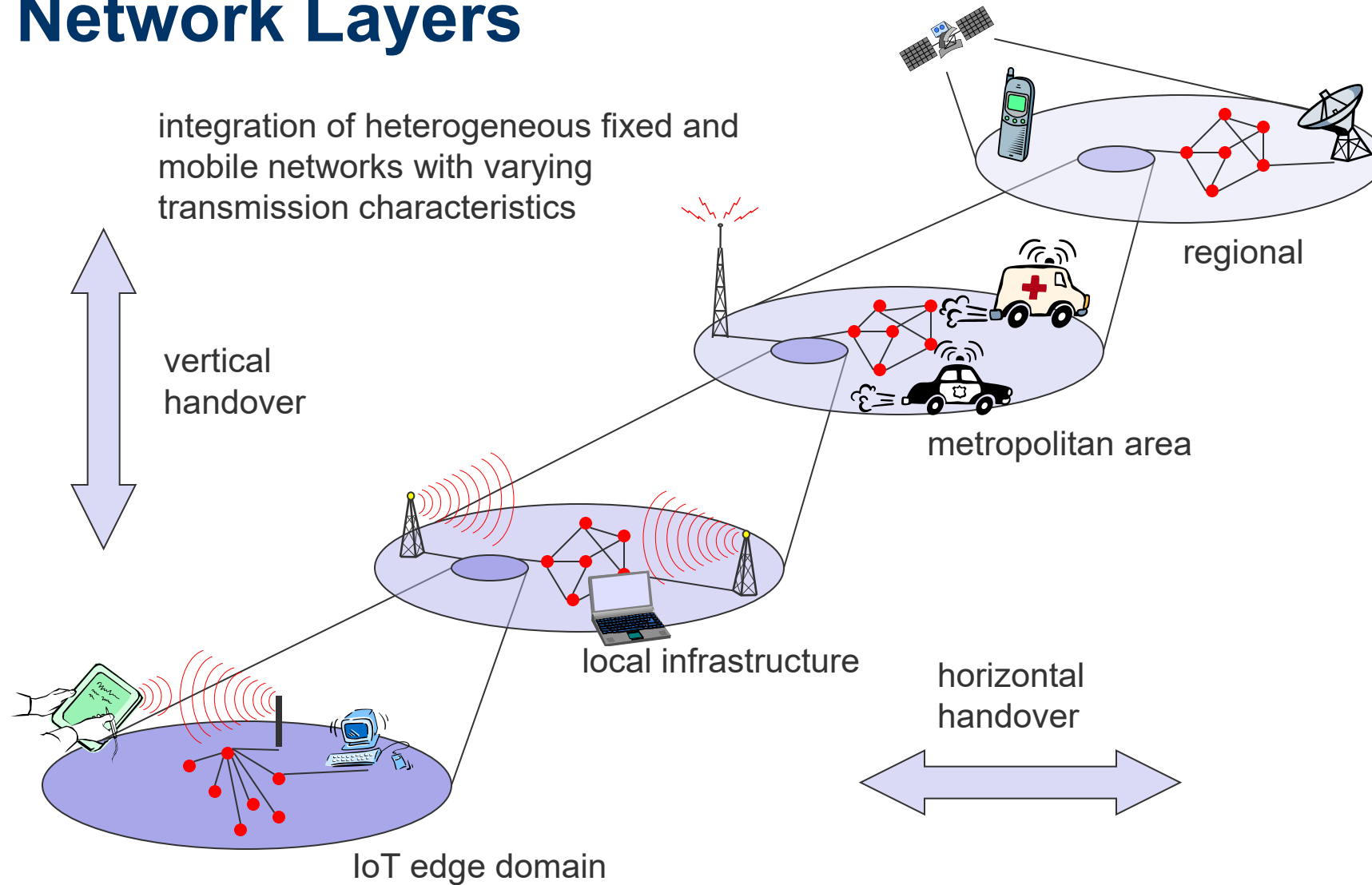
Two scenarios:

1. Mobile users with roaming infrastructure  
→ **Mobile IP(v6)**
2. Spontaneous networks of (autonomous) edge devices  
→ **the IoT scenario**



LONDON 1783:  
THE FIRST PROTOTYPE OF THE WIRELESS GALLOWS

# The Global View: Overlay Network Layers



# Mobile Ad Hoc Networks

Formed by wireless hosts which may be mobile

Without (necessarily) using a pre-existing infrastructure

Routes between nodes may potentially contain multiple hops

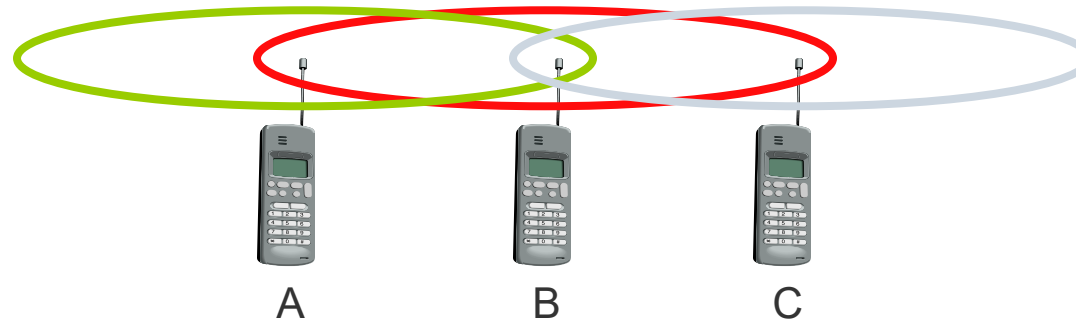
Motivations:

- Ease of deployment, low costs
- Speed of deployment
- Decreased dependence on infrastructure

# Hidden and exposed terminals

## Hidden terminals

- A sends to B, C cannot receive A
- C wants to send to B, C senses a “free” medium (CS fails)
- collision at B, A cannot receive the collision (CD fails)
- A is “hidden” for C



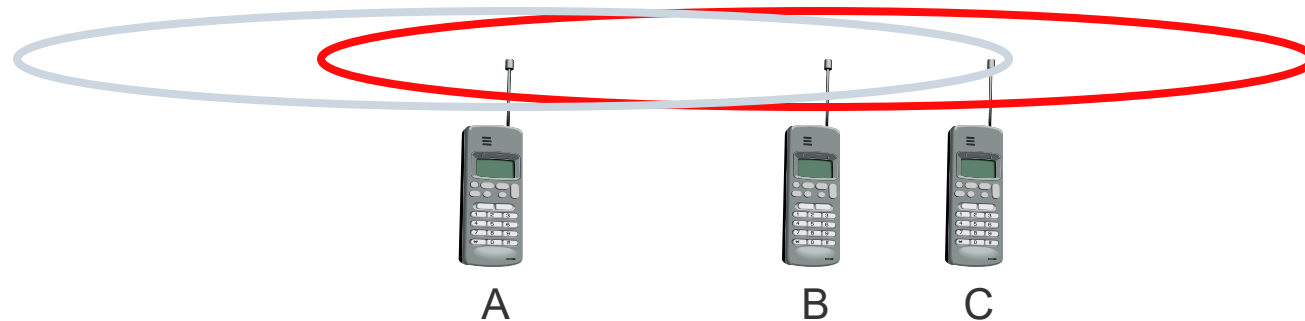
## Exposed terminals

- B sends to A, C wants to send to another terminal (not A or B)
- C has to wait, CS signals a medium in use
- but A is outside the radio range of C, therefore waiting is not necessary
- C is “exposed” to B

# Near and far terminals

Terminals A and B send, C receives

- signal strength decreases proportional to the square of the distance
- the signal of terminal B therefore drowns out A's signal
- C cannot receive A



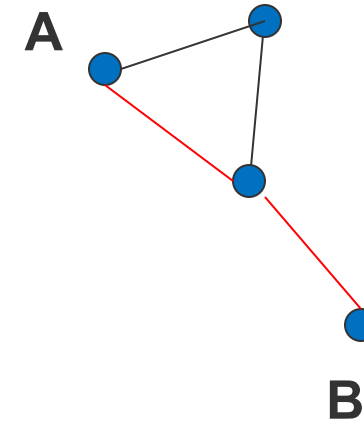
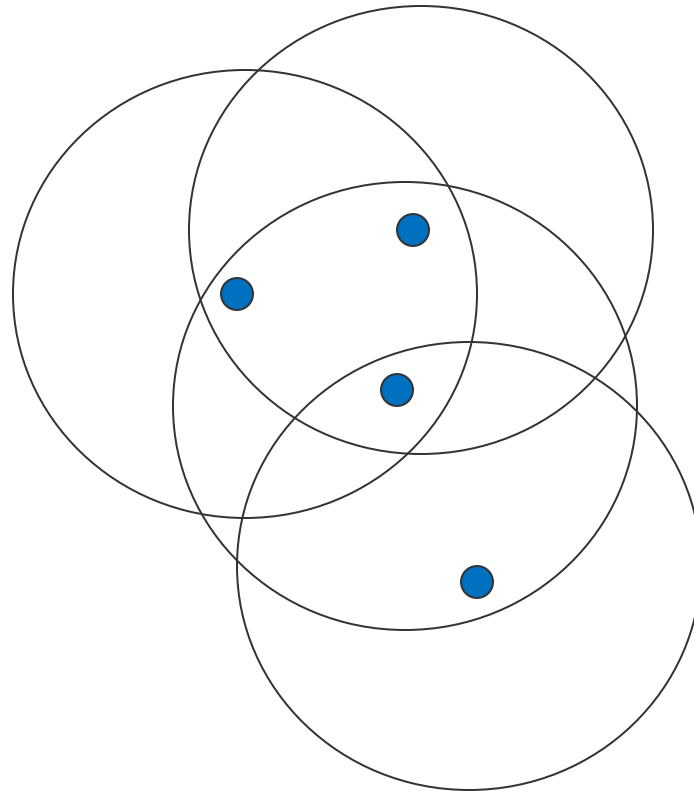
If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer

Also severe problem for CDMA-networks - precise power control needed!



# Multi-hop Topologies

May need to traverse multiple wireless links to reach a destination



# Two Solution Spaces

IP on the single link

- Single-hop solution
- Adaptation to constraints

IP for multi-hop traversal

- Routing protocol
- Changing topologies due to link degradation and mobility

# Low Power Lossy Wireless

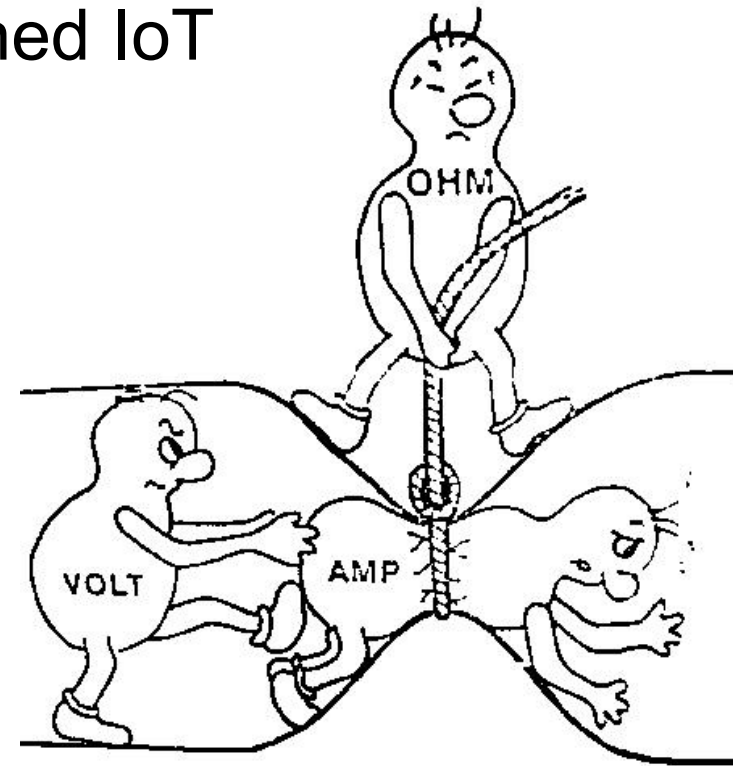
Default networking for the constrained IoT

Typically battery operated

Key problem: **energy consumption**

Low power leads to loss

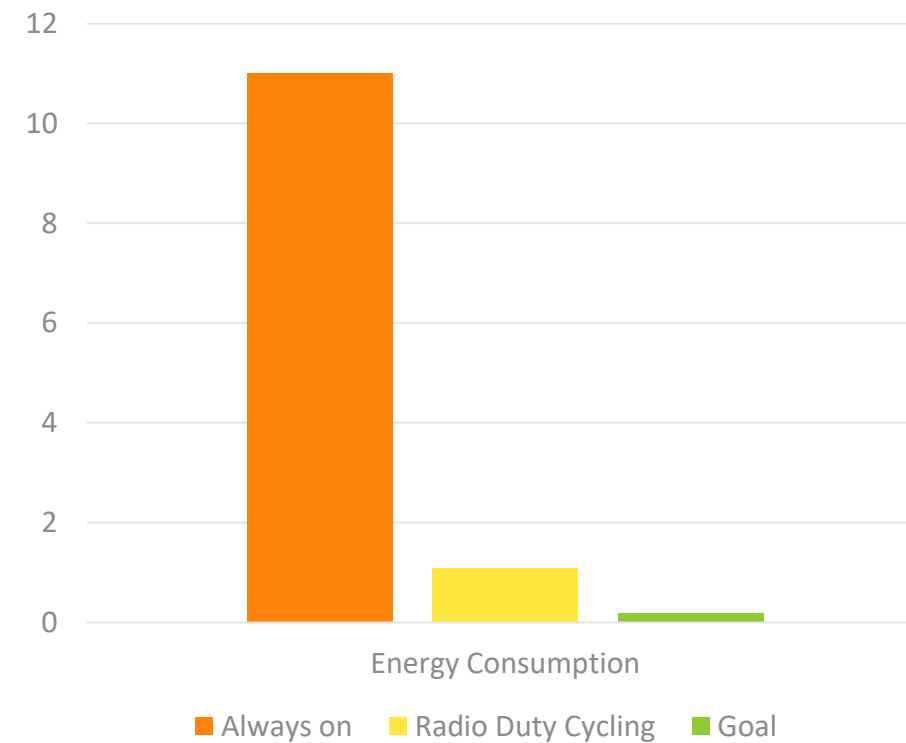
Transmission capabilities  
are weak



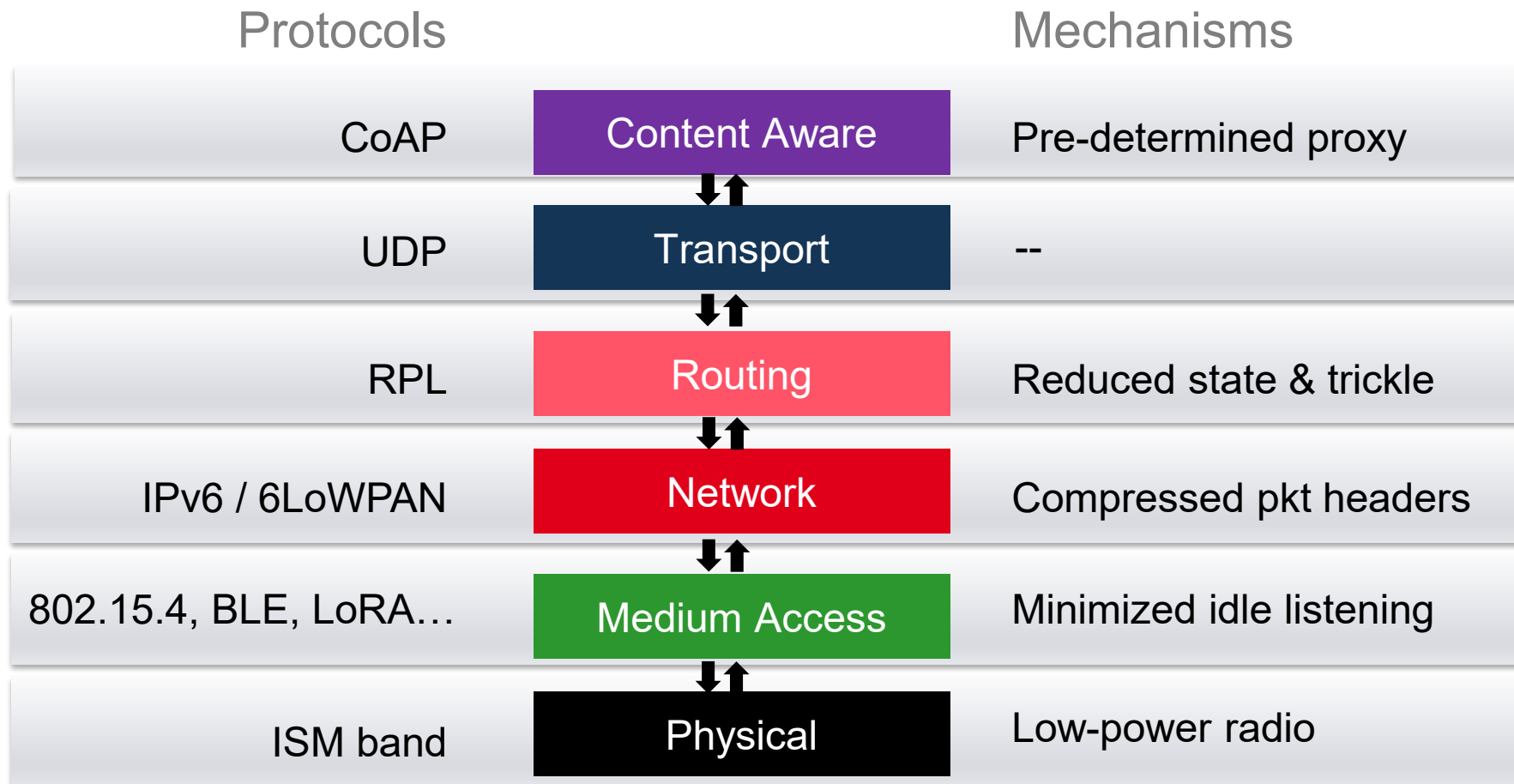
# How to Reduce the Radio Energy Consumption?



# How to Reduce the Radio Energy Consumption?



# Energy Savings along the IoT Protocol Stack



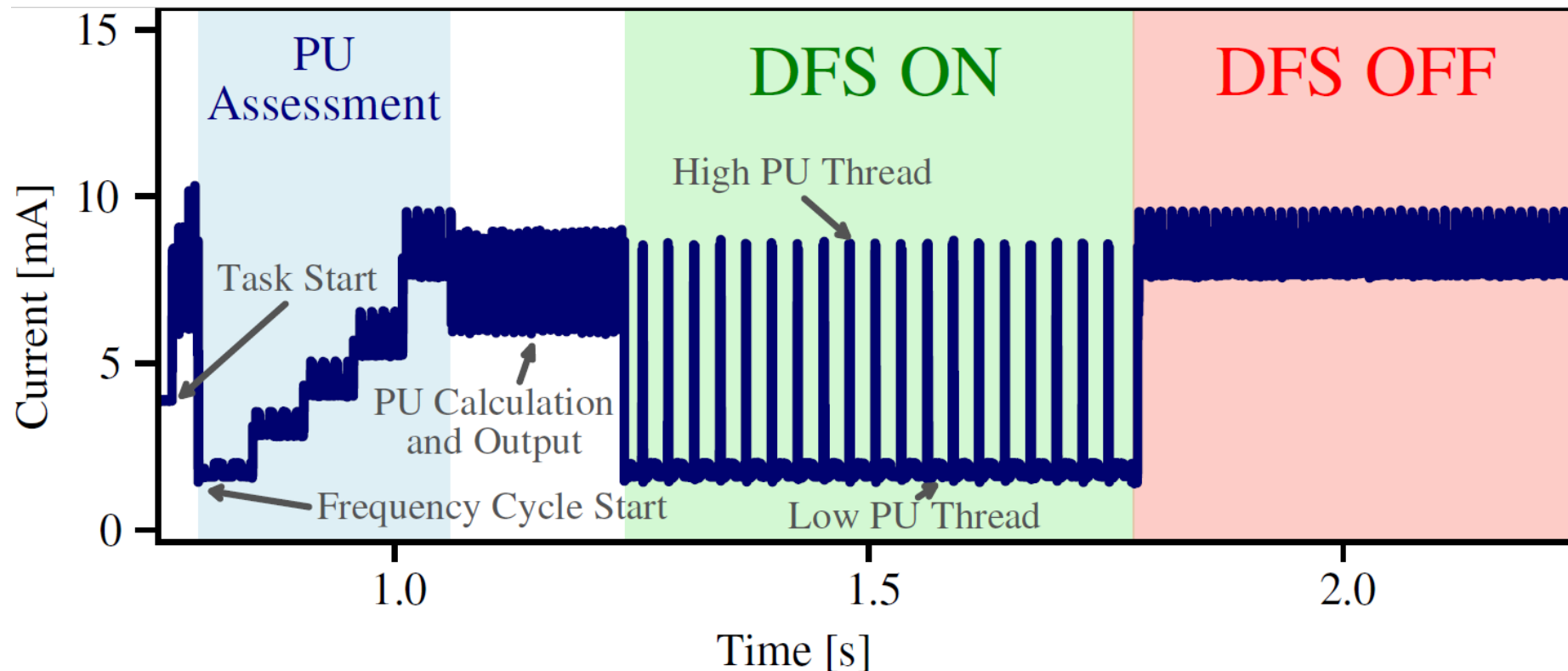


# Physical Aspect: Duty Cycling

- Switch peripherals to sleep between cycles of duty
- Different levels of sleep (board-dependent), some can handle interrupts
- Deep sleep in networking may lead to packet loss in unsynchronized scenarios

# System Aspect: Dynamic Voltage and Frequency Scaling

- DVFS adapts clock speed to task demands
- Voltage may then be reduced for slower clock ticks



# Dynamic Clock Reconfiguration for the Constrained IoT and its Application to Energy-efficient Networking

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## Abstract

Clock configuration takes a key role in tuning constrained general-purpose microcontrollers for performance, timing accuracy, and energy efficiency. Configuring the underlying clock tree, however, involves a large parameter space with complex dependencies and dynamic constraints. We argue for clock configuration as a generic operating system module that bridges the gap between highly configurable but complex embedded hardware and easy application development. In this paper, we propose a method and a runtime subsystem for dynamic clock reconfiguration on constrained Internet of Things (IoT) devices named ScaleClock. ScaleClock derives measures to dynamically optimize clock configurations by abstracting the hardware-specific clock trees. The Scale-

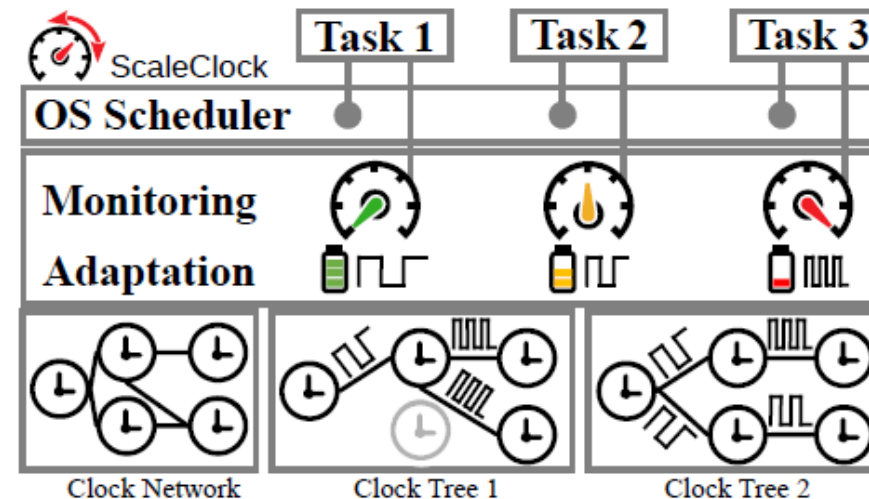


Figure 1: ScaleClock derives tasks characteristics at runtime

Michel Rottleuthner, Thomas C. Schmidt, Matthias Wählisch,

**Dynamic Clock Reconfiguration for the Constrained IoT and its Application to Energy-efficient Networking,**

**In:** *Proc. of Embedded Wireless Systems and Networks (EWSN'22)*, p. 168–179, ACM : New York, USA, October 2022.

# Link Layer Aspects

Inherently unreliable due to wireless medium

Small frame size: ~100 Bytes

Low bandwidth: ~100 kbit/s

Topologies include star and mesh

Networks are ad hoc & devices have limited accessibility

Typical radios

- Short range: IEEE 802.15.4, Bluetooth Low Energy (BLE)
- Long range: NB-IoT, LoRA

# IEEE 802.15.4

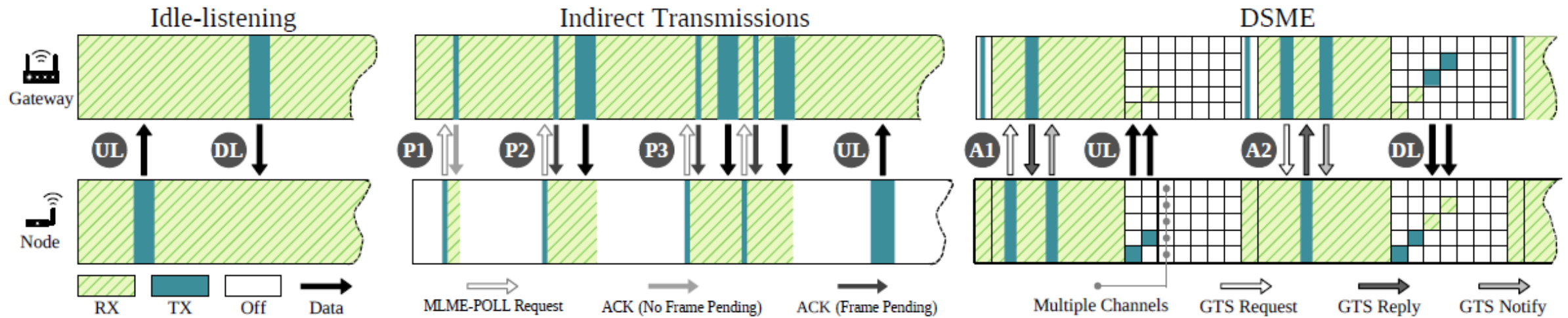
Common low-power radio

- Lower layer of Zigbee and (some) Xbee
- IP convergence layer: 6LoWPAN

Characteristics of 802.15.4:

- Frequencies: 868 MHz, 915 MHz, 2.4 GHz
- 16-bit short or IEEE 64-bit extended MAC addresses
- Entire 802.15.4 frame size is 127 bytes, 25 bytes frame overhead
- Bandwidth ranges from 20 to 250 kbit/s
- Outreach ranges from 1 to 100 m
- 802.15.4 subnets may utilize multiple radio hops

# IEEE 802.15.4: Different Types of MAC Operations





# LoRa

Long range radio communication technology

- typical transmission range 5 – 15 km

Frequency (ISM) band depends on region

Duty cycle of 1% / channel

Modulation robust and configurable

- adjusts Range, Time on Air, energy consumption

Semi-proprietary technology by SEMTECH

- LoRa Alliance with ~ 200 members

# Three LoRa Device Classes

## Class A

Only receive  
after send

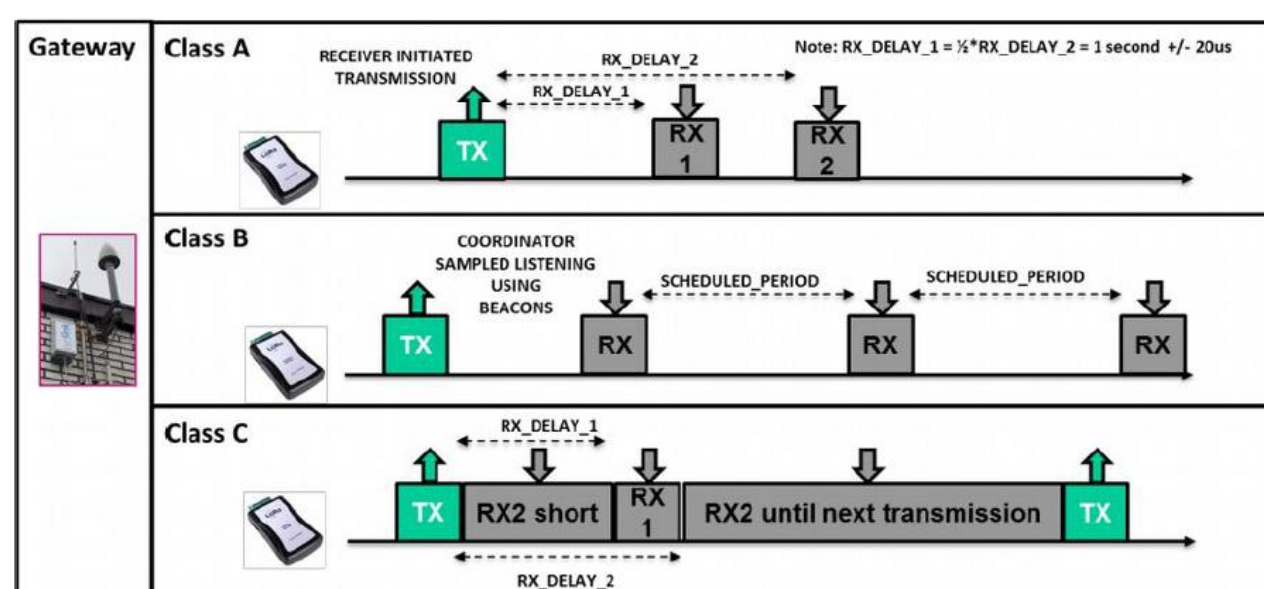
Very low power  
consumption

## Class B

Receive windows  
scheduled

## Class C

Always listen  
Highest power  
consumption



<https://link.springer.com/article/10.1007/s11277-017-4419-5>

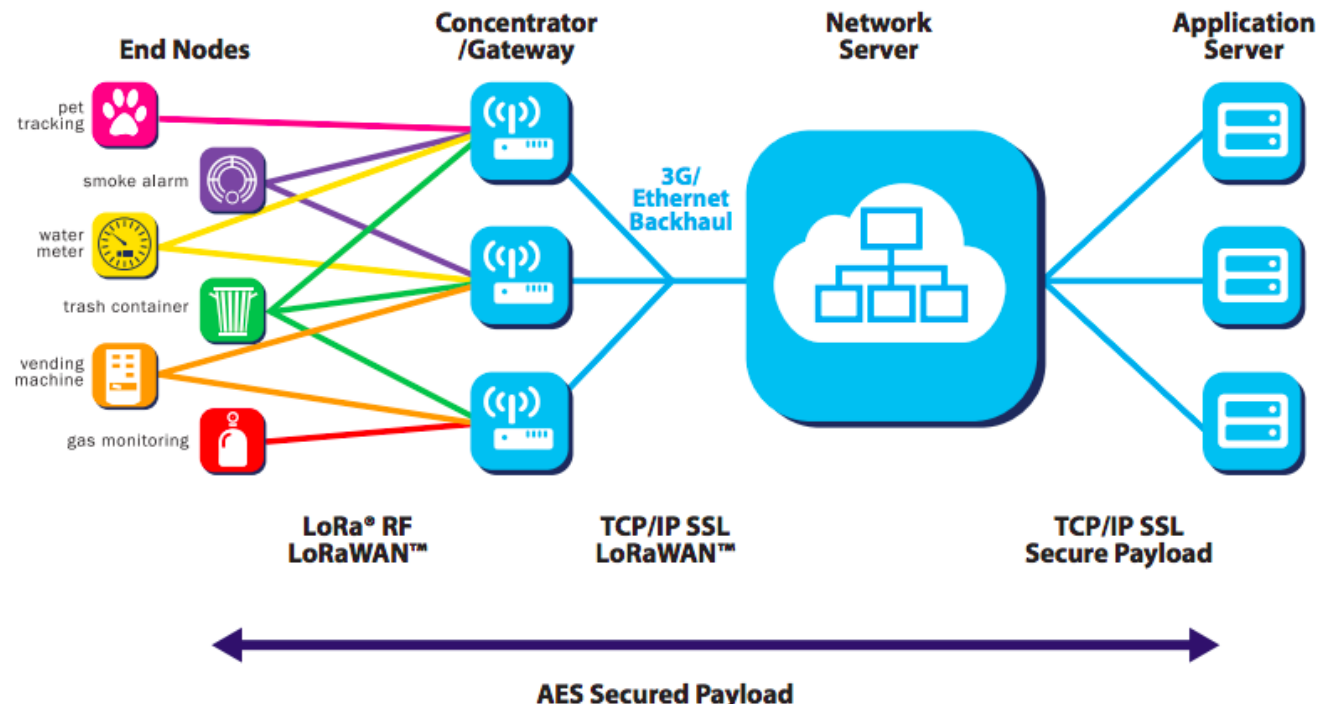
# LoRa: IP-Embedding by LoRaWAN

**End nodes:** Transmit to Gateways

**Gateways:** Transparently relay (tunnel)

**Network Server:** De-duplicates and routes to application

**Application:** Holds security association



Low power long range IPv6 networking

# UNLOCKING LORA

# LoRa vers. LoRaWAN

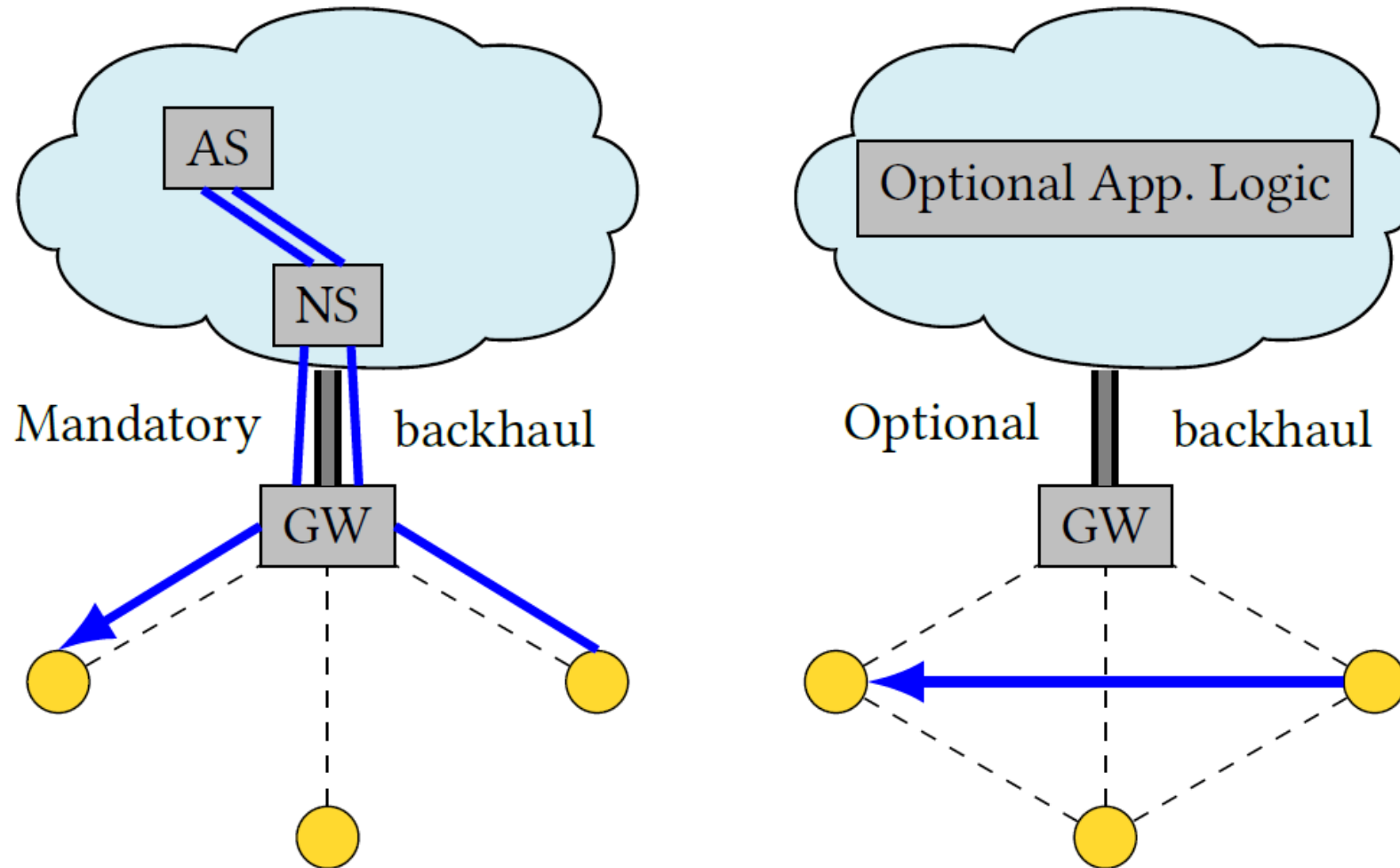
LoRa wireless modulation:

- Long range transmission (up to 15 kms)
- Low power consumption (mJ)
- Low data rate (bytes/s)

LoRaWAN cloud-based network emulation:

- Centralized
- Uplink-oriented, no P2P
- Unbound transmission delays

# LoRa: Client-to-Client Communication?

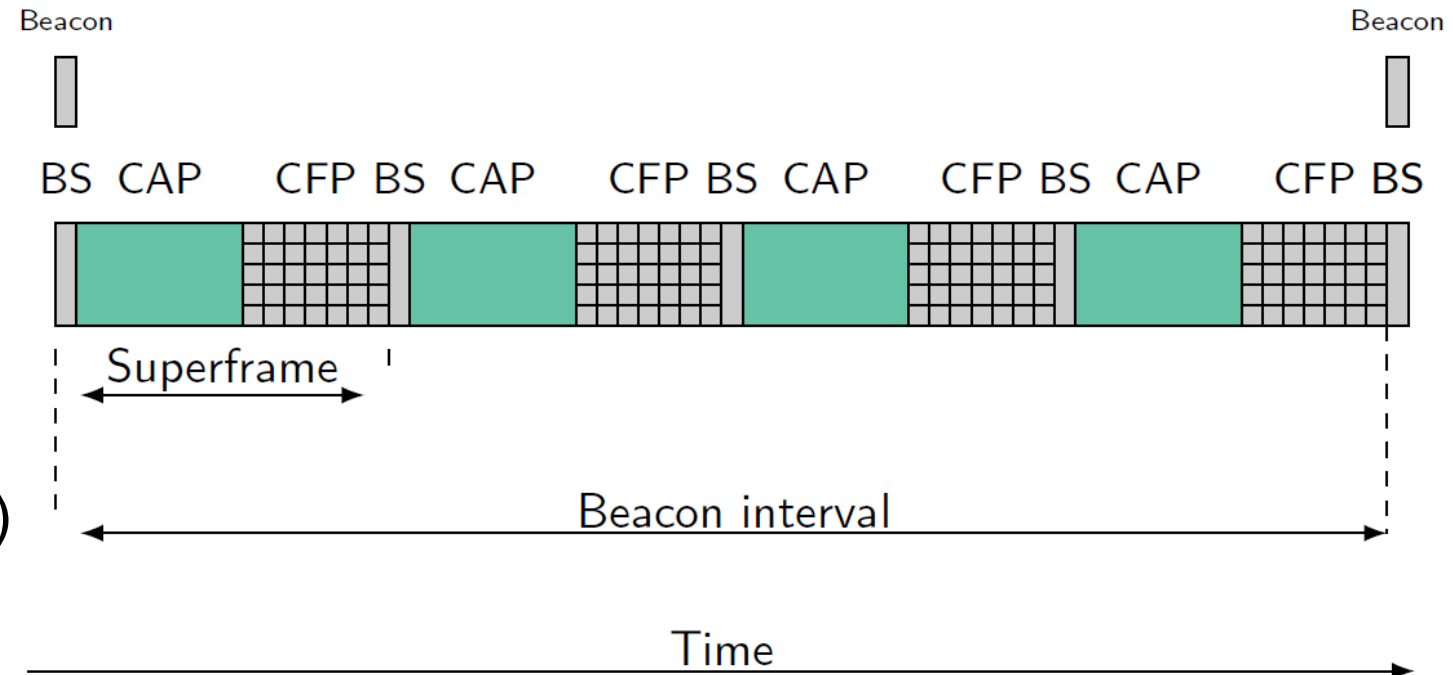




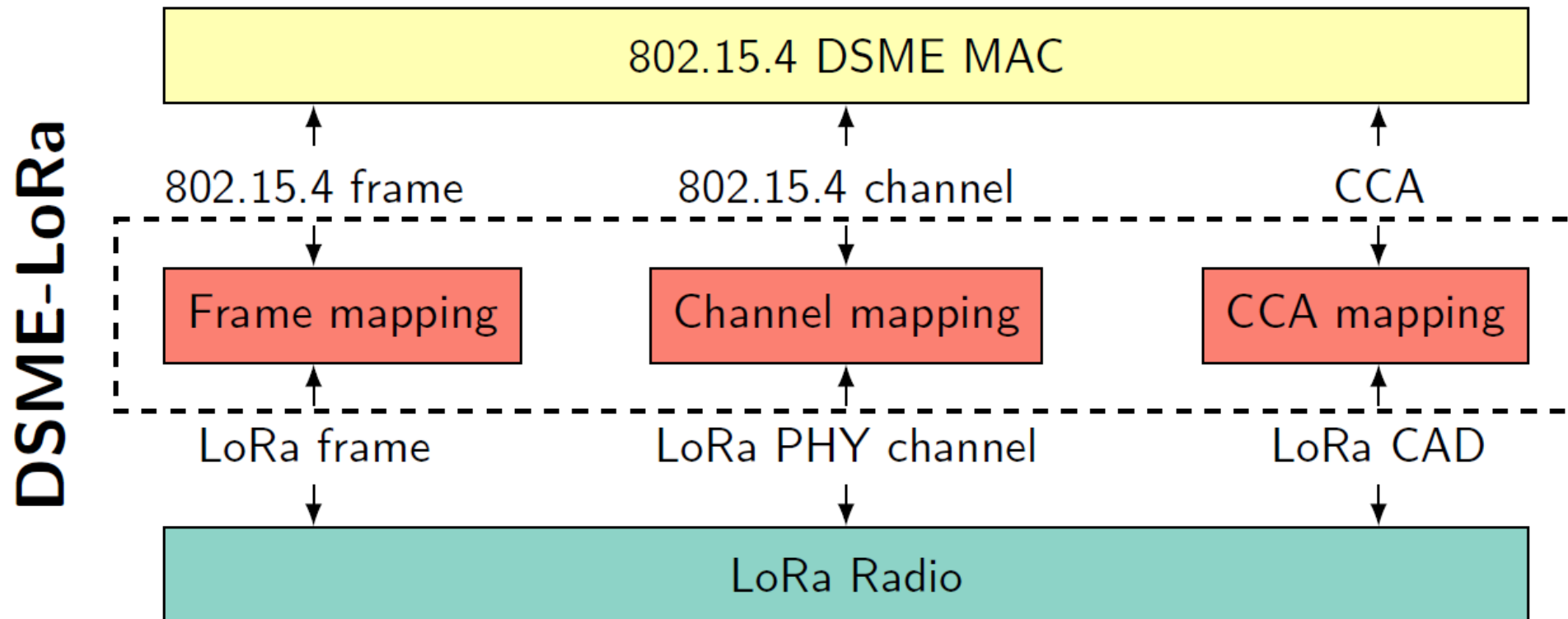
# DSME MAC

- Deterministic Synchronous Multichannel Extensions
- Standard MAC-Layer from IEEE 802.15.4
- Configurably combines
  - Contention access (CAP)
  - Contention free access (CFP)

## DSME Multiframe Structure



# DSME-LoRa

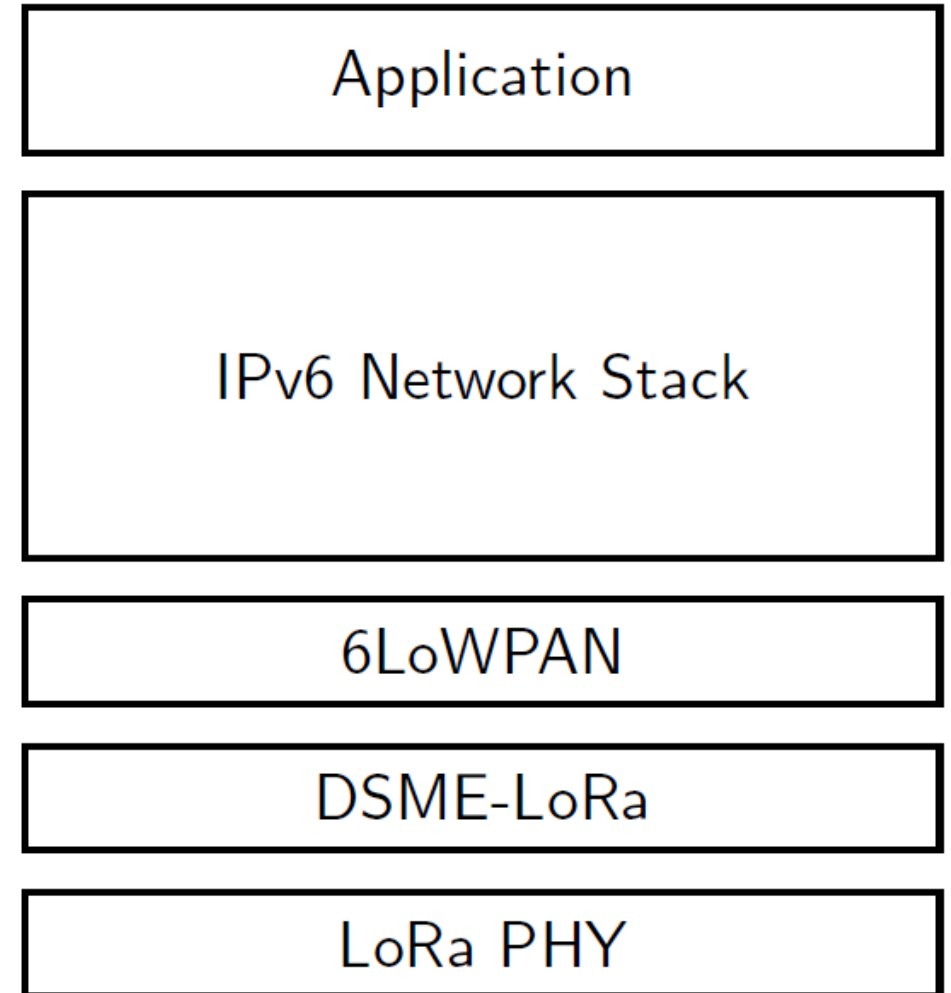


# 6LoRa: Transmission of IPv6 Packets over LoRa

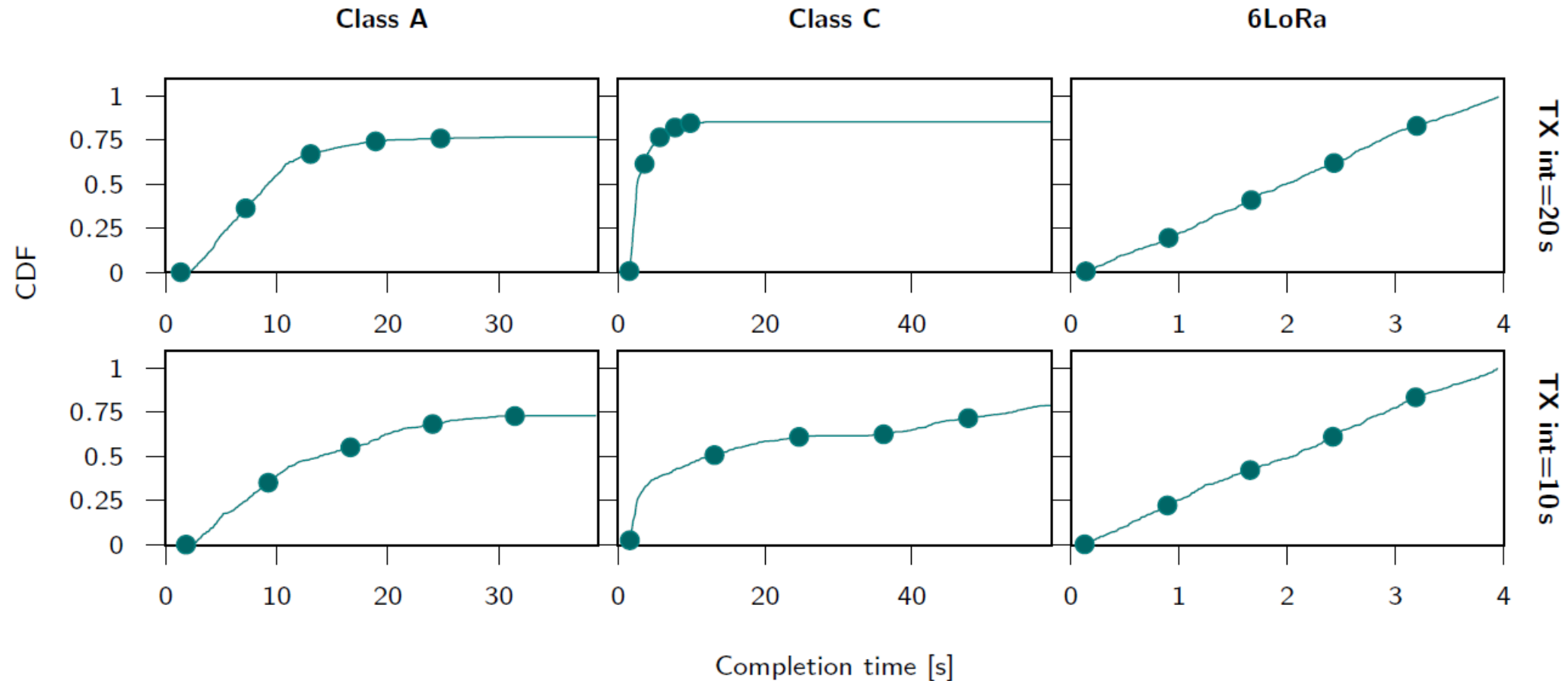
- IETF 6LoWPAN<sup>a</sup> for IPv6 transmission over IEEE 802.15.4
- Inherit 6LoWPAN roles

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<sup>a</sup>RFC 6282. September 2011.



# 6LoRa Performance: Packet Reception



# Energy Consumption

| Device   | TXi [s] | Power [mW]     |                |       |
|----------|---------|----------------|----------------|-------|
|          |         | SCHC-LoRaWAN   |                | 6LoRa |
|          |         | <i>Class A</i> | <i>Class C</i> |       |
| Sensor   | 20      | 0.49           | 12.87          | 1.33  |
| Sensor   | 10      | 0.87           | 13.3           | 2.04  |
| Actuator | -       | 0.54           | 12.41          | 2.93  |

# DSME-LoRa: Seamless Long Range Communication Between Arbitrary Nodes in the Constrained IoT

JOSÉ ÁLAMOS, PETER KIETZMANN, and THOMAS C. SCHMIDT, HAW Hamburg, Germany  
MATTHIAS WÄHLISCH, Freie Universität Berlin, Germany

Long range radio communication is preferred in many IoT deployments as it avoids the complexity of multi-hop wireless networks. LoRa is a popular, energy-efficient wireless modulation but its networking substrate LoRaWAN introduces severe limitations to its users. In this paper, we present and thoroughly analyze DSME-LoRa, a system design of LoRa with IEEE 802.15.4 Deterministic Synchronous Multichannel Extension (DSME) as a MAC layer. DSME-LoRa offers the advantage of seamless client-to-client communication beyond the pure gateway-centric transmission of LoRaWAN. We evaluate its feasibility via a full-stack implementation on the popular RIOT operating system, assess its steady-state packet flows in an analytical stochastic Markov model, and quantify its scalability in massive communication scenarios using large scale network simulations. Our findings indicate that DSME-LoRa is indeed a powerful approach that opens LoRa to standard network layers and outperforms LoRaWAN in many dimensions.

CCS Concepts: • **Computer systems organization** → **Sensor networks**; • **Networks** → **Link-layer protocols**; *Network performance analysis*.

Additional Key Words and Phrases: Internet of Things, wireless, LPWAN, MAC layer, network experimentation

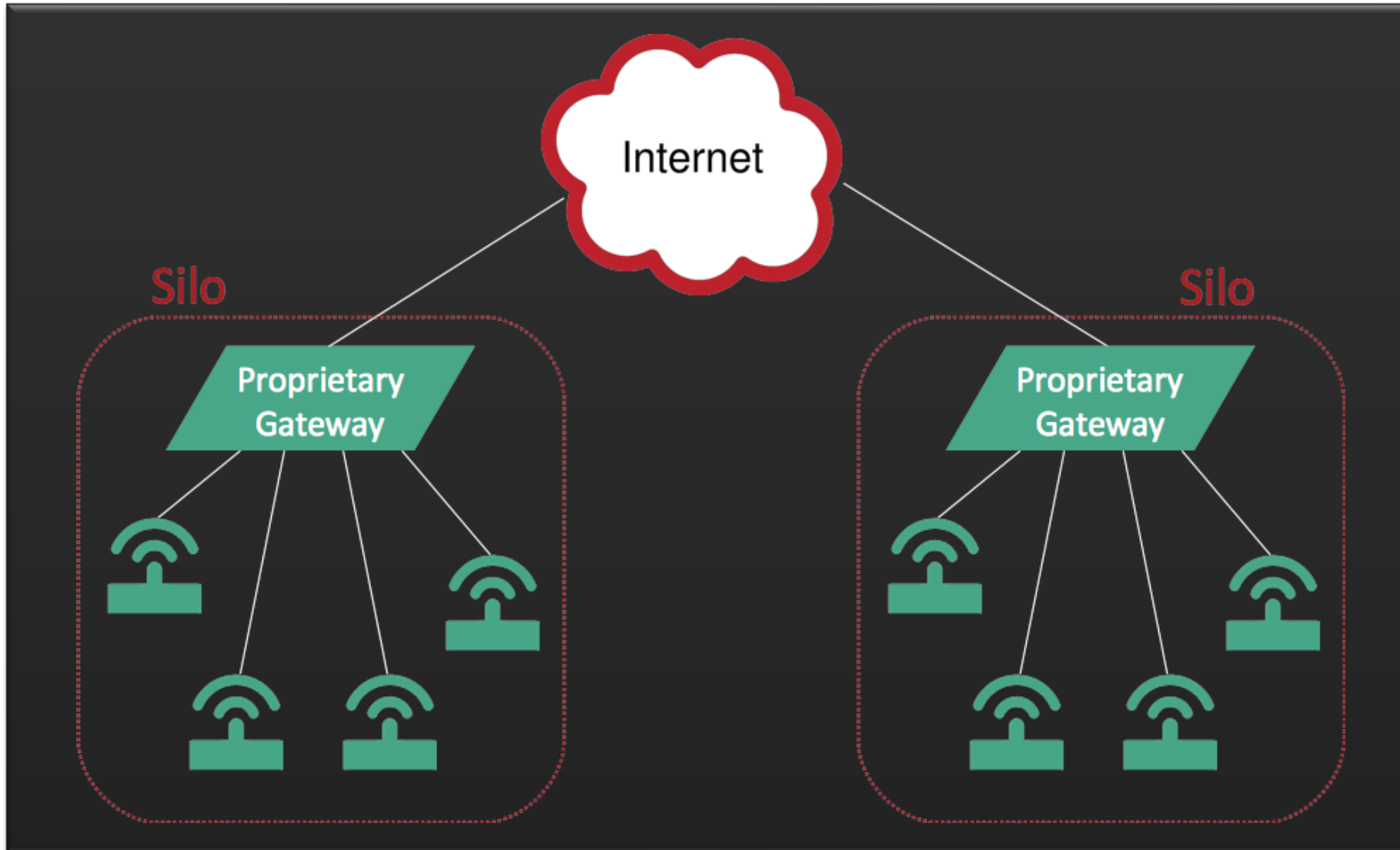
Jose Alamos, Peter Kietzmann, Thomas C. Schmidt, Matthias Wählisch,  
**DSME-LoRa: Seamless Long Range Communication Between Arbitrary Nodes in the Constrained IoT**,  
*Transactions on Sensor Networks (TOSN)*, Vol. **18**, No. 4, p. 1–43, ACM : New York, USA, November 2022.

# Agenda

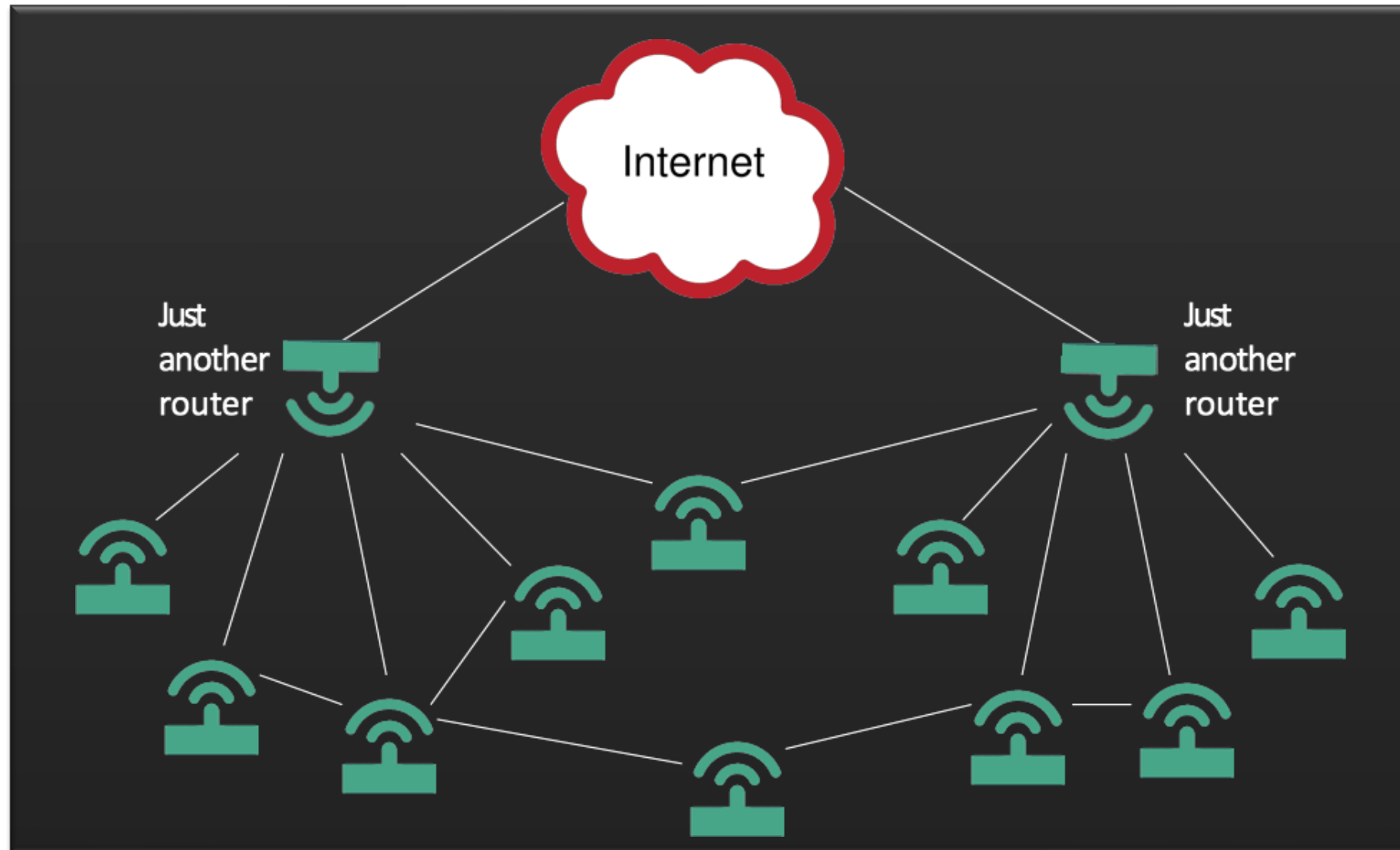
- 🕒 The Internet of Things
- 🕒 IoT on Wireless Link Layers
- 🕒 IP in the Internet of Things
  - ➡ Architectural Challenges
  - ➡ 6LoWPAN Adaptation Layer
  - ➡ Application-Layer Protocols



# The IoT today looks mostly like this



# The IoT we want looks more like that



# The IoT we want is... the Internet!



# The Difference

## Network level interoperability

- End-to-end connectivity per default
  - Device-to-device connectivity
- => No more walls!

## System level interoperability

- Efficient hardware-independent software
  - No device lock-down
- => No more waste!

# IP in the Internet of Things

100+ Billion microcontrollers exist worldwide  
(in contrast to several hundred million Internet devices)

- Rapid growths and demands for *scalable* connectivity
- Integrate into the global Internet with E2E data flows
- Interoperable, long-lived, reliable standards required: **IP++**

Link-layers are different

- All wireless, dedicated technologies

Constraint Communication: Low Power Lossy Networks (LLN)

- Measures of Bytes ... instead of Megabytes

Constraint Devices: Microcontrollers

- Measures of kHz and kByte
- Often on batteries



# What is 6LoWPAN

IPv6 over Low-Power ( $\supset$  Personal) wireless Area Networks

- Declare IPv6 a distinct network layer

A transparent way to integrate embedded devices into the global Internet

- Global addressing
- E2E transport between embedded and core devices

IPv6 adaptation to LLNs

- Stateless and stateful header compression
- Optimized neighbor discovery
- Standard Socket API

# Challenges of LoWPAN

| Impact Analysis                                | Addressing                        | Routing                                    | Security                             | Network management                            |
|------------------------------------------------|-----------------------------------|--------------------------------------------|--------------------------------------|-----------------------------------------------|
| Low power<br>(1-2 years lifetime on batteries) | Storage limitations, low overhead | Periodic sleep aware routing, low overhead | Simplicity (CPU usage), low overhead | Periodic sleep aware management, low overhead |
| Low cost<br>(<\$10/unit)                       | Stateless address generation      | Small or no routing tables                 | Ease of Use, simple bootstrapping    | Space constraints                             |
| Low bandwidth<br>(<300kbps)                    | Compressed addresses              | Low routing overhead                       | Low packet overhead                  | Low network overhead                          |
| High density<br>(<2-4? units/sq ft)            | Large address space – IPv6        | Scalable and routable to *a node*          | Robust                               | Easy to use and scalable                      |
| IP network interaction                         | Address routable from IP world    | Seamless IP routing                        | Work end to end from IP network      | Compatible with SNMP, etc                     |

Source: Kushalnagar/Montenegro@IETF62



# Protocol Stack

**TCP/IP Protocol Stack**

|              |     |      |  |
|--------------|-----|------|--|
| HTTP         |     | RTP  |  |
| TCP          | UDP | ICMP |  |
| IP           |     |      |  |
| Ethernet MAC |     |      |  |
| Ethernet PHY |     |      |  |

Application

Transport

Network

Data Link

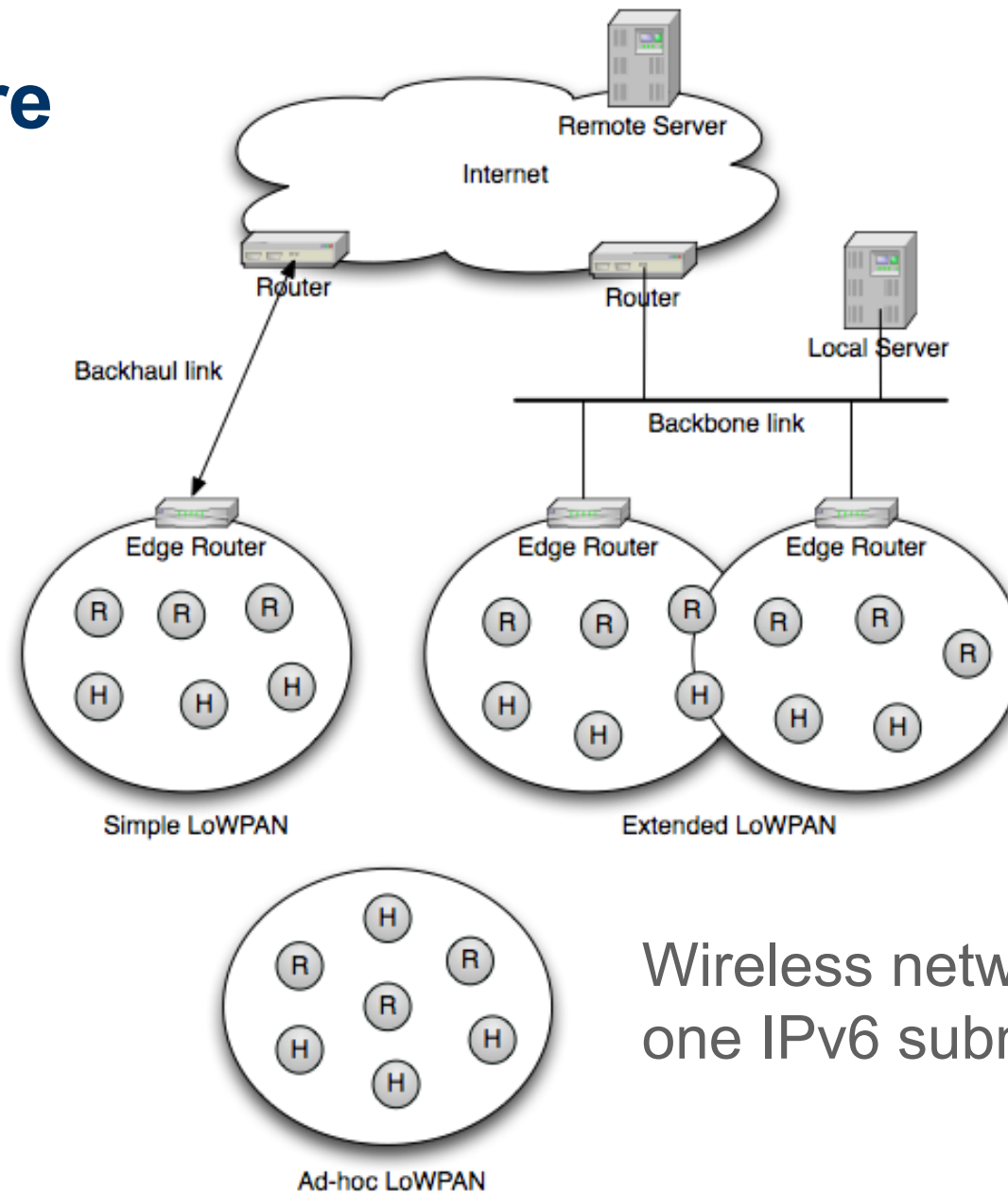
Physical

**6LoWPAN Protocol Stack**

|                   |      |
|-------------------|------|
| Application       |      |
| UDP               | ICMP |
| IPv6 with LoWPAN  |      |
| IEEE 802.15.4 MAC |      |
| IEEE 802.15.4 PHY |      |

Source: Shelby & Bormann – 6LoWPAN, Wiley 2011

# Architecture



Wireless network is  
one IPv6 subnet

Source: Shelby & Bormann – 6LoWPAN, Wiley 2011

# Architecture

LoWPANs are stub networks

Simple LoWPAN

- Single Edge Router

Extended LoWPAN

- Multiple Edge Routers with common backbone link

Ad-hoc LoWPAN

- No route outside the LoWPAN

Internet integration issues

- Maximum transmission unit
- Application protocols
- IPv4 interconnectivity
- Firewalls and NATs
- Security

| IPv6         |                   |
|--------------|-------------------|
| Ethernet MAC | LoWPAN Adaptation |
|              | IEEE 802.15.4 MAC |
| Ethernet PHY | IEEE 802.15.4 PHY |

**IPv6-LoWPAN Router Stack**

# Key Problems

Efficient use of available bits in a packet

- Frame: 127 bytes – 25 bytes L2 header
- IPv6 header: 40 bytes, UDP header: 8 bytes

...

IPv6 MTU size  $\geq 1280$

- IP packets need transparent fragmentation on frames
- Lost fragments cause retransmission of entire packet

Wireless ad hoc networks can be multihop

- No direct router link  $\leftrightarrow$  Router Advertisement
- Multicast is only local  $\leftrightarrow$  Neighbor Discovery

## Base Solution: RFC 4944

Makes 802.15.4 look like an IPv6 link:

Efficient encapsulation

- Stateless IP/UDP header compression of intra-packet redundancy
- Unicast + Multicast address mapping

Adaptation layer for fragmentation (1280 MTU on ~100 bytes packets)

- Fragmentation: Datagram tag + offset
- No dedicated fragment recovery

Mesh forwarding

- Link generated by „mesh-under“ (L2) routing
- Identify originator and final destination

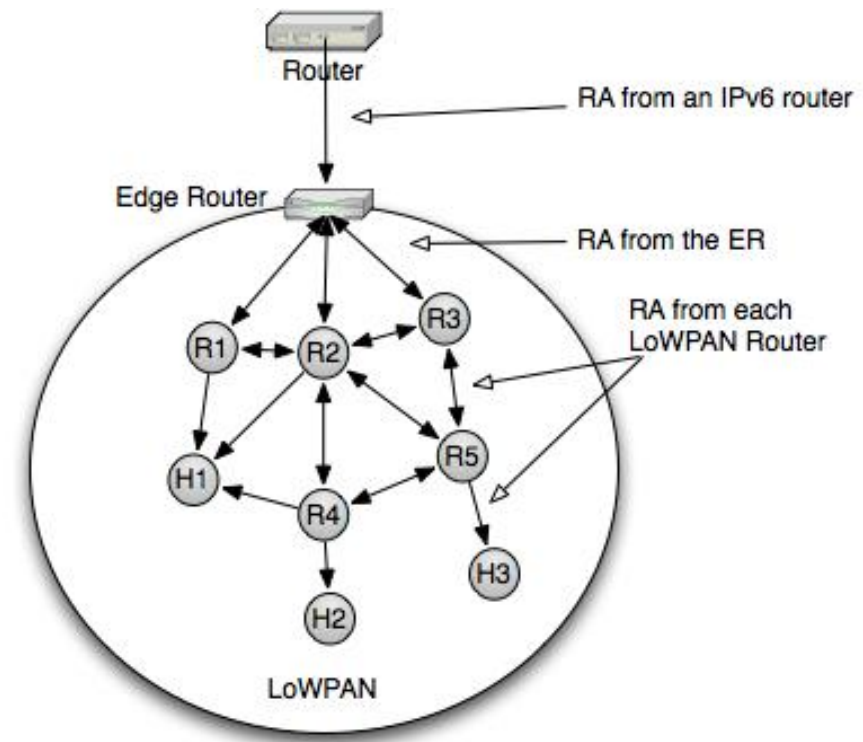
# Adaptive Neighbor Discovery RFC 6775

Includes „route-over“ (L3 routing)

Multihop forwarding of Router Advertisements  
(GW and prefix dissemination)

Address Registration and  
Confirmation at Router

Router keeps track of  
wireless nodes (incl. DAD)



# Typical 6LowPAN-ND Exchange

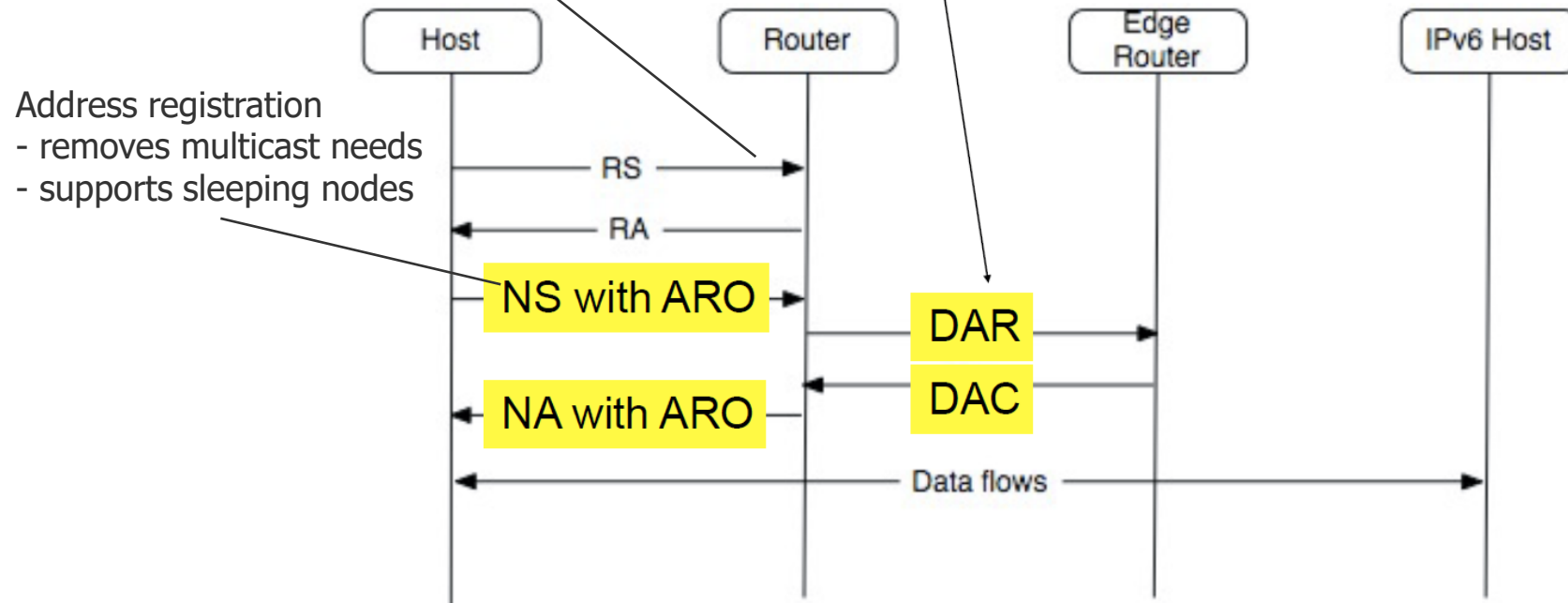
Solicited router advertisement only

- removes periodic Router Advertisements
- includes 6LowPAN context option

Optional multi-hop DAD

Address registration

- removes multicast needs
- supports sleeping nodes



Authoritative Border Router Option (ABRO) to distribute prefix and context across a route-over network



# Improved Header Compression RFC 6282

Router Advertisements distribute a well-known area context

- Common prefix – LoWPAN is a flat network
- 6LoWPAN-HC – header compression methods

No addresses – Interface Identifiers derived from MAC addresses

- Optional unicast and multicast address fields (compressed)

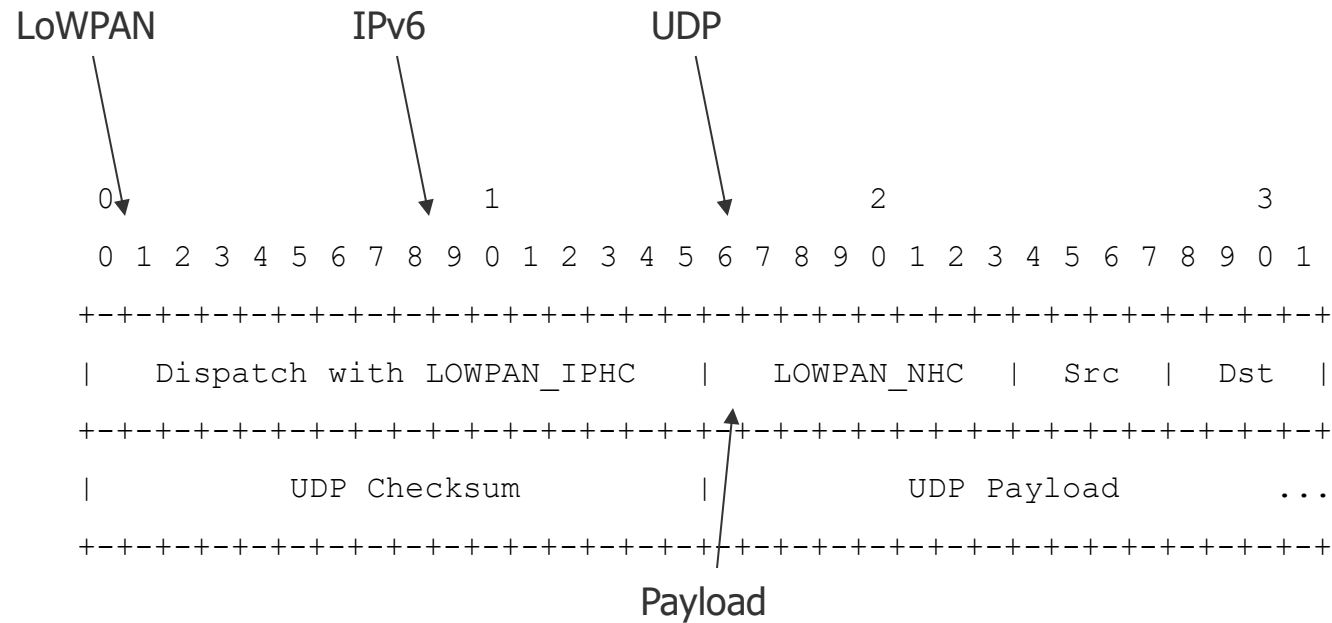
Remaining IPv6 header fields compressed or elided

- Length derived from frame, ToS and Flow Label elided

Stateless UDP header compression including short ports and selected checksum removal

- Length derived from frame length

# LoWPAN UDP/IPv6 Headers

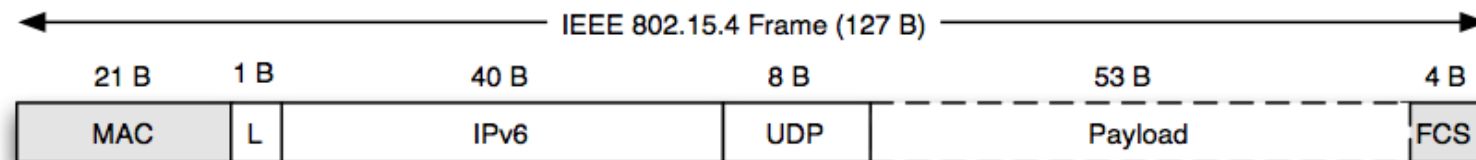


6 Bytes!

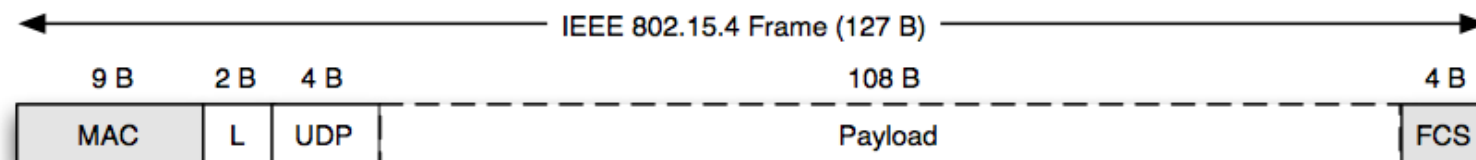
# 6LoWPAN Headers

Orthogonal header format for efficiency

Stateless header compression



**Full UDP/IPv6 (64-bit addressing)**



**Minimal UDP/6LoWPAN (16-bit addressing)**

Source: Shelby & Bormann – 6LoWPAN, Wiley 2011

# CoAP: Constrained Application Protocol

Constrained machine-to-machine Web protocol  
Representational State Transfer (REST)  
architecture

Simple proxy and caching capabilities

Asynchronous transaction support

Low header overhead and parsing complexity

URI and content-type support

UDP binding (may use IPsec or DTLS)

Reliable unicast and best-effort multicast support

Built-in resource discovery

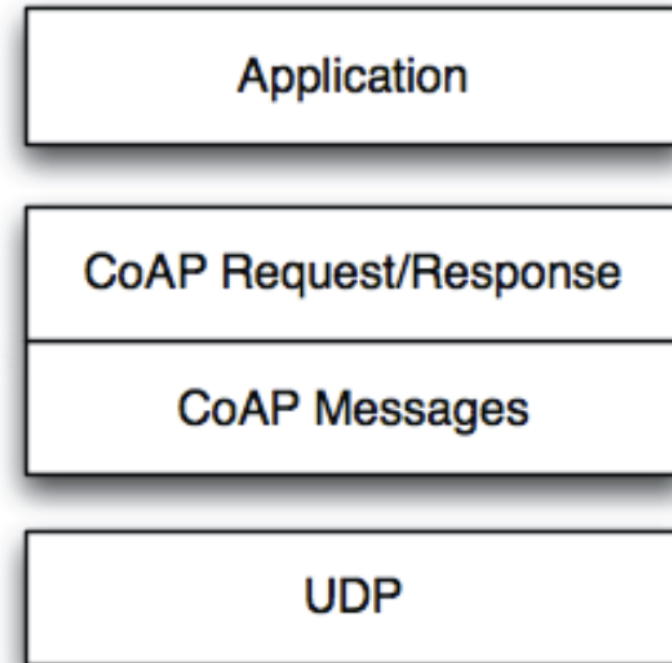
# COAP Message Semantic

Four messages:

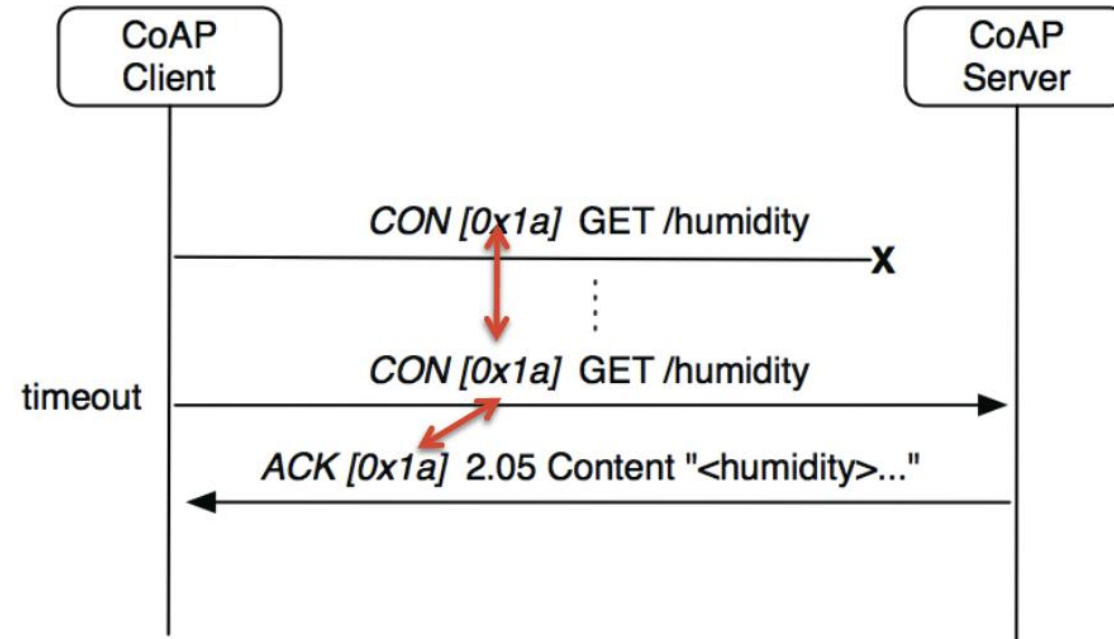
- Confirmable (**CON**)
- Non-Confirmable (**NON**)
- Acknowledgement (**ACK**)
- Un-processing (**RST**)

REST Request/Response  
piggybacked on CoAP Messages

Methods: **Get**, **Put**, **Post**, **Delete**  
– Several extensions defined



# Message Transactions, Packet Loss

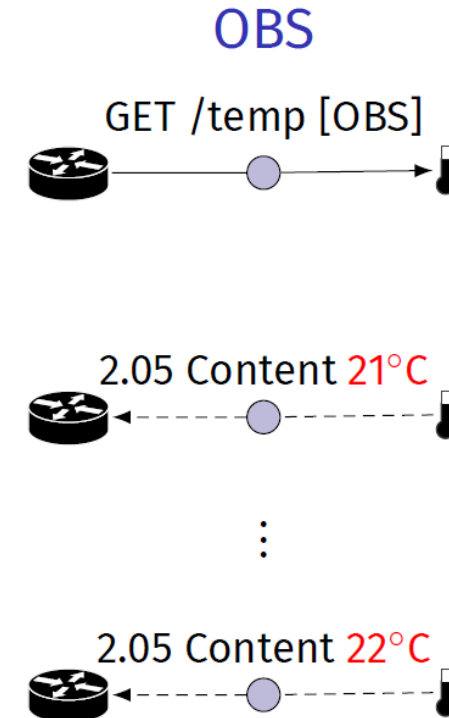
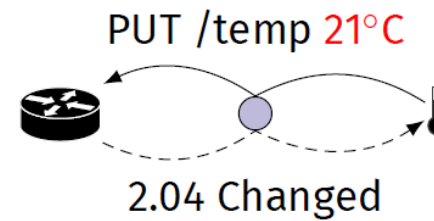
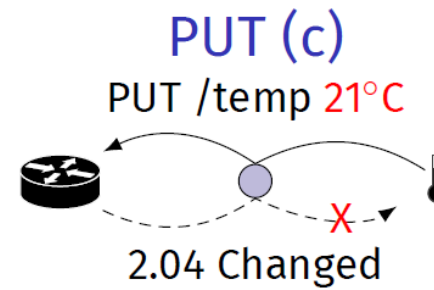
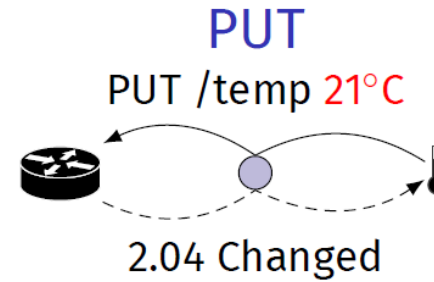
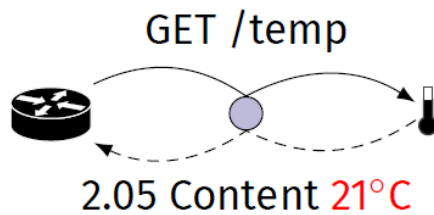
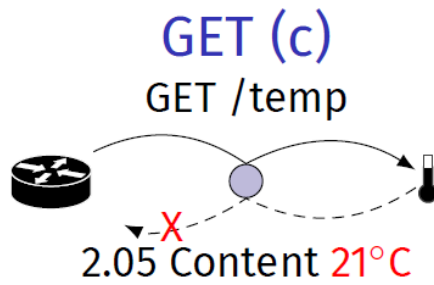
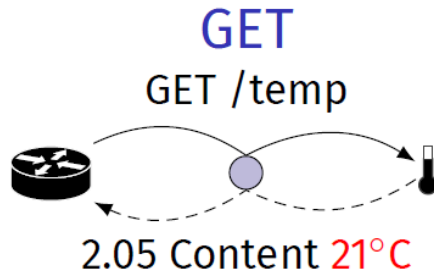


Each message carries an ID (transactional processing) and an optional token (for asynchronous matching)

Stop and Wait approach

Repeat a request in case ACK (or RST) is not coming back

# CoAP Operational Modes





# MQTT: Message Queuing Telemetry Transport

Publish-subscribe protocol (IBM 1999)

Lightweight & simple on top of TCP/IP

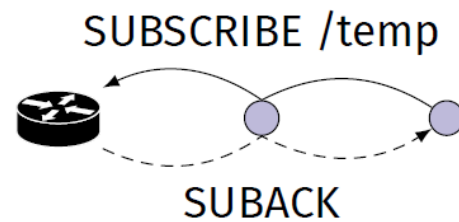
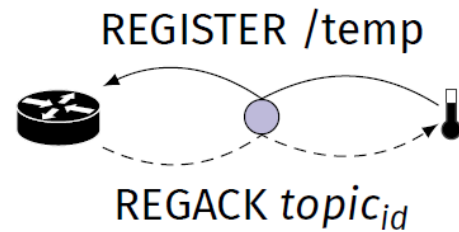
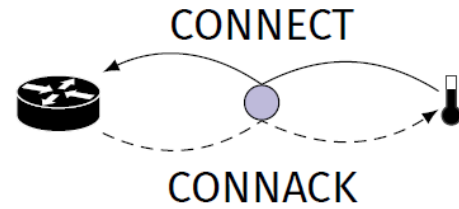
MQTT-SN – UDP-based variant for the IoT

Publishers and subscribers exchange data via a Broker

Different quality levels:

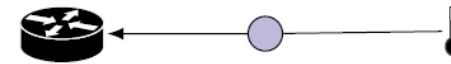
- Q0 – unreliable
- Q1 – reliable (at least once)
- Q2 – reliable (exactly once)

# MQTT-SN Operational Modes



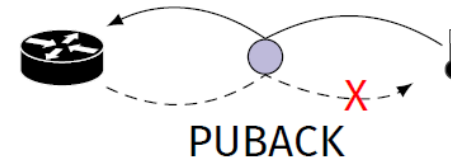
Q0

PUBLISH  $topic_{id}$  21°C

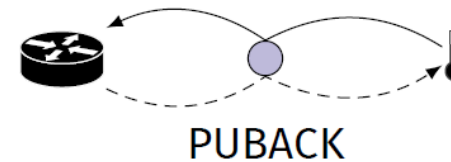


Q1

PUBLISH  $topic_{id}$  21°C



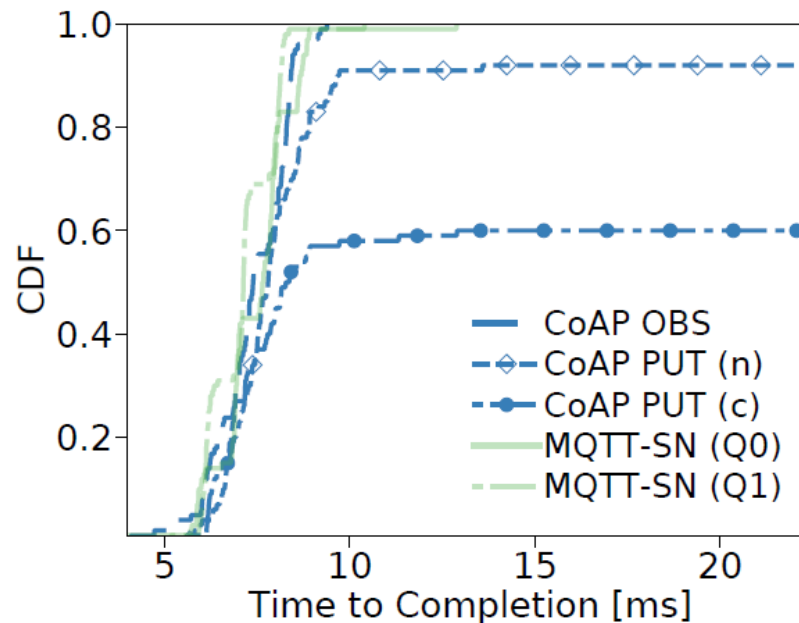
PUBLISH  $topic_{id}$  21°C



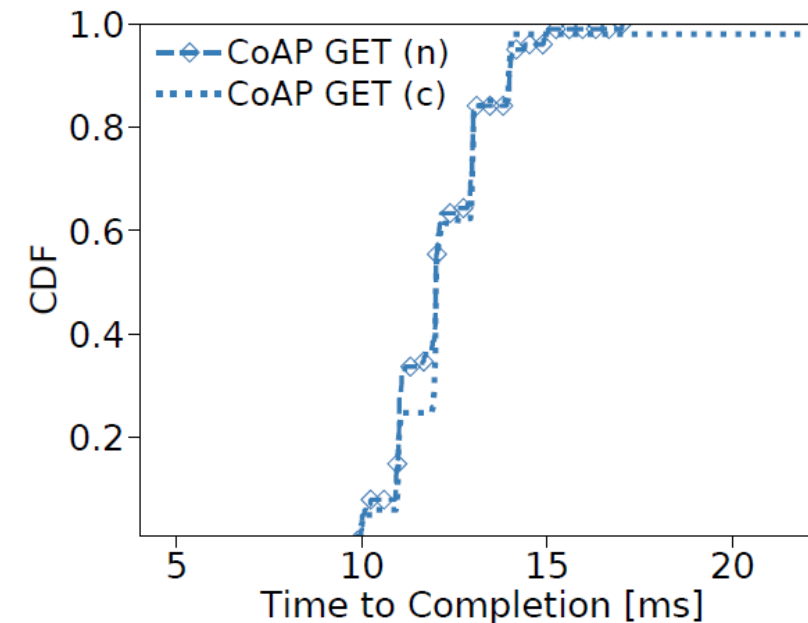
# Performance Comparison

## Experiments in a Single Hop Testbed

Time to content arrival for **scheduled** publishing every 50 ms



Push protocols



Pull protocols

## Further Aspects & Activities

6LoWPAN on Blue Tooth Low Energy & Lora

Application Layer Encoding: CBOR

- RFC 7049 Concise Binary Object Representation
- Minimal code size, small message sizes, no deflation
- Based on the JSON data model

DNS over CoAP: [draft-ietf-core-dns-over-coap](#)

Things Description: IoT Semantics

Widely implemented:



**Contiki**



# Bibliography

1. Internet Society: *The Internet of Things: An Overview*, White Paper, Oct. 2015  
<http://www.internetsociety.org/doc/iot-overview>
2. Zach Shelby, Carsten Bormann: *6LoWPAN: The Wireless Embedded Internet*, Wiley & Sons, 2009.
3. Michel Rottleuthner, Thomas C. Schmidt, Matthias Wählisch, *Dynamic Clock Reconfiguration for the Constrained IoT and its Application to Energy-efficient Networking*, In: *Proc. of Embedded Wireless Systems and Networks (EWSN'22)*, p. 168–179, ACM : New York, USA, October 2022.
4. Jose Alamos, Peter Kietzmann, Thomas C. Schmidt, Matthias Wählisch, *DSME-LoRa: Seamless Long Range Communication Between Arbitrary Nodes in the Constrained IoT*, *Transactions on Sensor Networks (TOSN)*, Vol. 18, No. 4, p. 1–43, Nov. 2022.
5. C. Gündogan, P. Kietzmann, M. Lenders, H. Petersen, T. Schmidt, M. Wählisch, *NDN, CoAP, and MQTT: A Comparative Measurement Study in the IoT*, *Proc. of 5th ACM Conference on Information-Centric Networking (ICN)*, Sept. 2018.
6. Drafts, RFCs: [tools.ietf.org](https://tools.ietf.org), <http://www.rfc-editor.org>