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

IoT: Connecting the Physical World to the Internet

Industrial Automation

Connected Vehicles

IoT: Connecting the Physical World to the Internet

Industrial Automation

Connected Vehicles

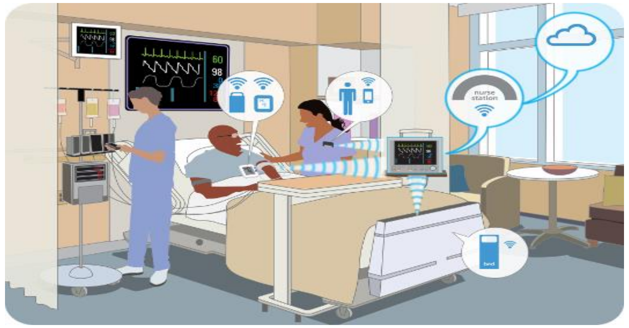
Smart Homes

IoT: Connecting the Physical World to the Internet

Industrial Automation

Connected Vehicles

Smart Homes



eHealth

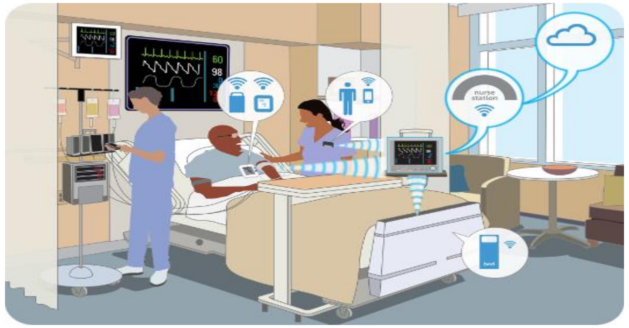
IoT: Connecting the Physical World to the Internet

Micro- & Nano Satellites

Industrial Automation

Connected Vehicles

Smart Homes



eHealth

Use Case: Security in Harsh Industrial Environments

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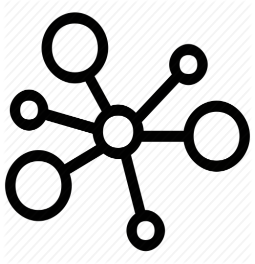
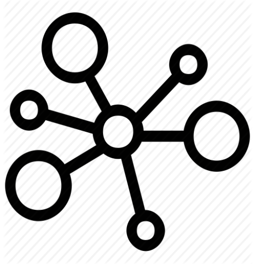
Use Case: Security in Harsh Industrial Environments





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
Controllers

Wireless
Networking

IPv4 Uplink
to the Cloud

Evolution Towards an IoT

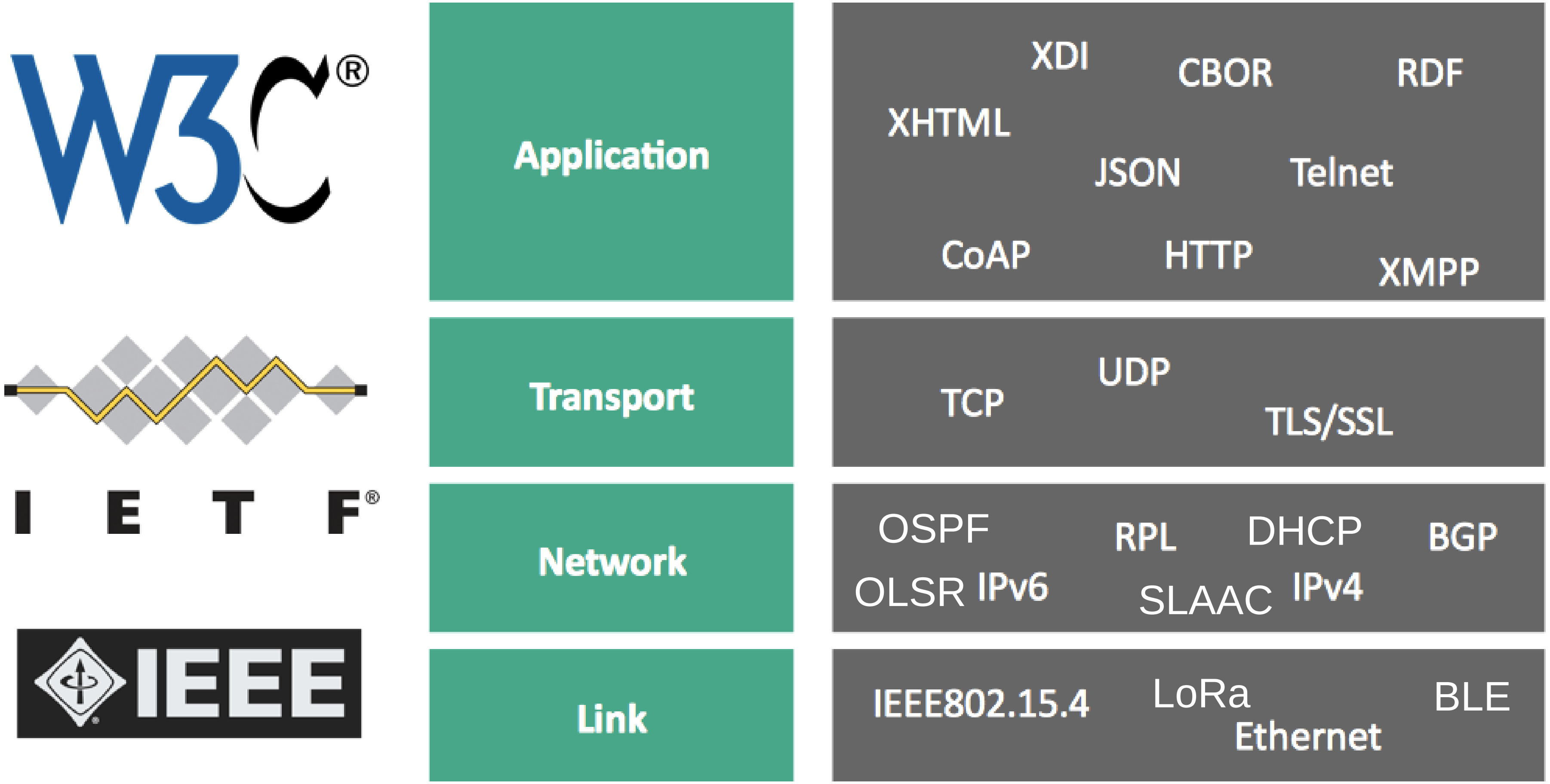
Distributed local intelligence		Wireless sensor network	
Embedded Controllers	+	**Wireless Networking**	**IPv4 Uplink to the Cloud**

Evolution Towards an IoT

Distributed local intelligence		Wireless sensor network		Internet of Things ?
Embedded Controllers	+	**Wireless Networking**	+	**IPv4 Uplink to the Cloud**

This is not yet an
Internet
of Things!

No Internet without Open Speech and Open Standards



Evolution towards an *Internet* oT

Distributed local intelligence		Wireless sensor network		Hype-Internet of Things
Embedded Controllers	+	**Wireless Networking**	+	**IPv4 Uplink to the Cloud**

Evolution towards an *Internet* oT

Distributed local intelligence | Wireless sensor network | Hype-Internet of Things

Embedded Controllers + **Wireless Networking** + **IPv4 Uplink to the Cloud**

+

Interoperable Information

Evolution towards an *Internet* oT

Distributed local intelligence		Wireless sensor network		Hype-Internet of Things
Embedded Controllers	+	**Wireless Networking**	+	**IPv4 Uplink to the Cloud**
+		+		
Interoperable Information	+	**Distributed Security**		

Evolution towards an *Internet* oT

Distributed local intelligence		Wireless sensor network		Hype-Internet of Things
Embedded Controllers	+	**Wireless Networking**	+	**IPv4 Uplink to the Cloud**
+		+		+
Interoperable Information	+	**Distributed Security**	+	**Things loosely joined by IPv6**

Evolution towards an *Internet* oT

Distributed local intelligence		Wireless sensor network		Hype-Internet of Things
Embedded Controllers	+	**Wireless Networking**	+	**IPv4 Uplink to the Cloud**
+		+		+
Interoperable Information	+	**Distributed Security**	+	**Things loosely joined by IPv6**

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

The many faces of the IoT

High-end IoT

Processor: GHz, 32/64 Bit
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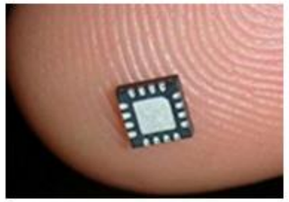
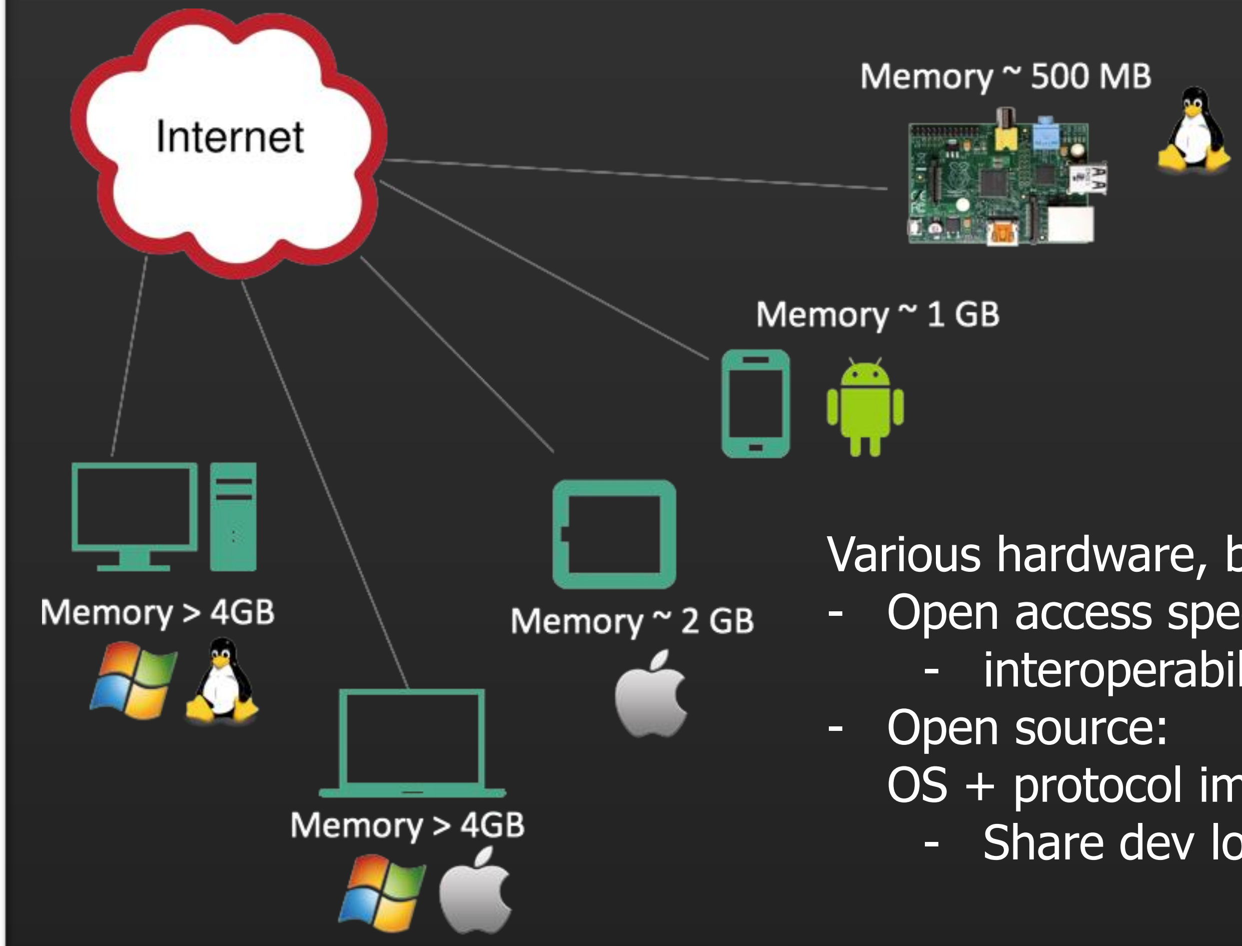
Low-end (or constrained) IoT



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

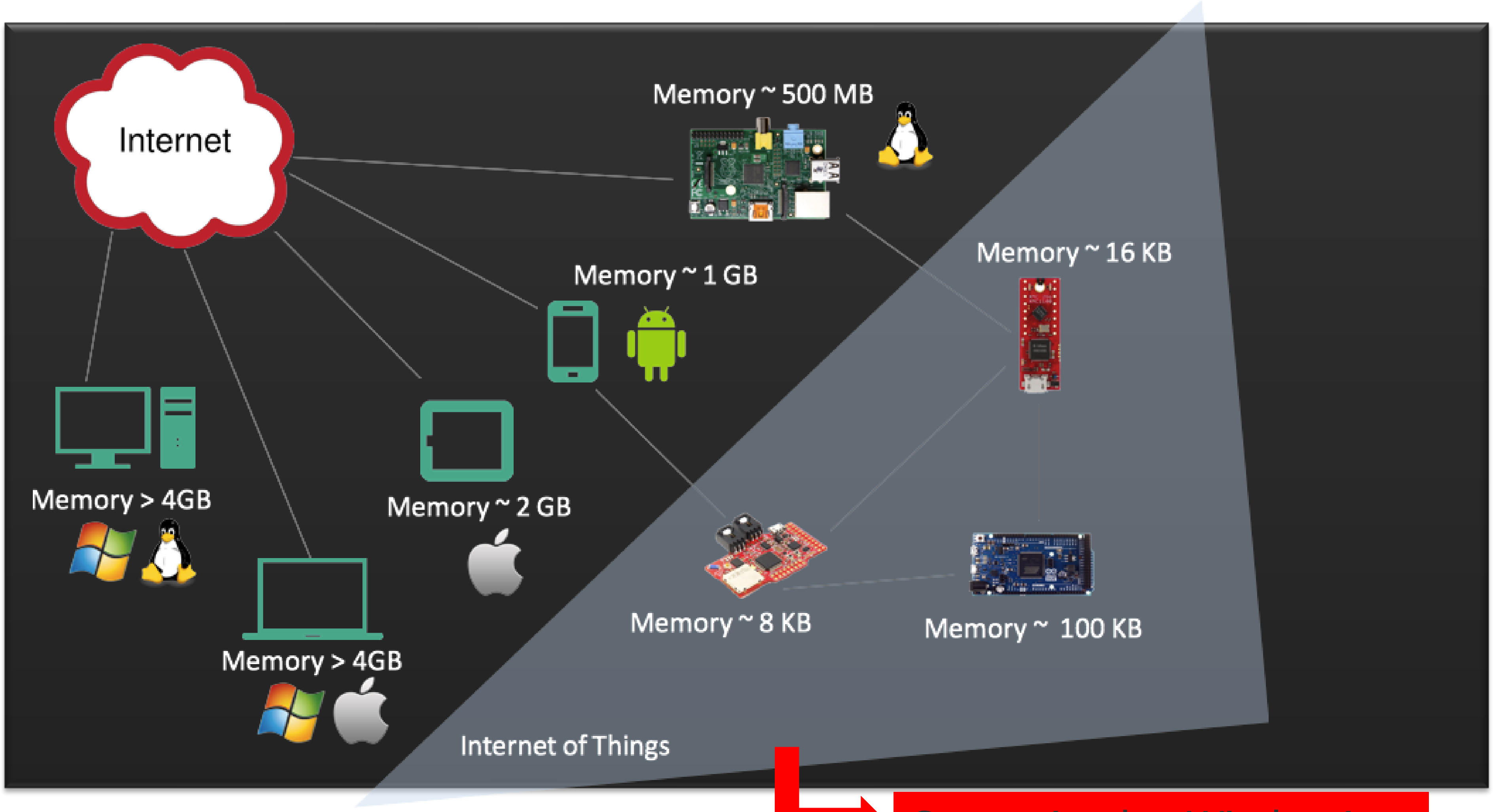
The Internet (as we know it)



Various hardware, but more importantly:

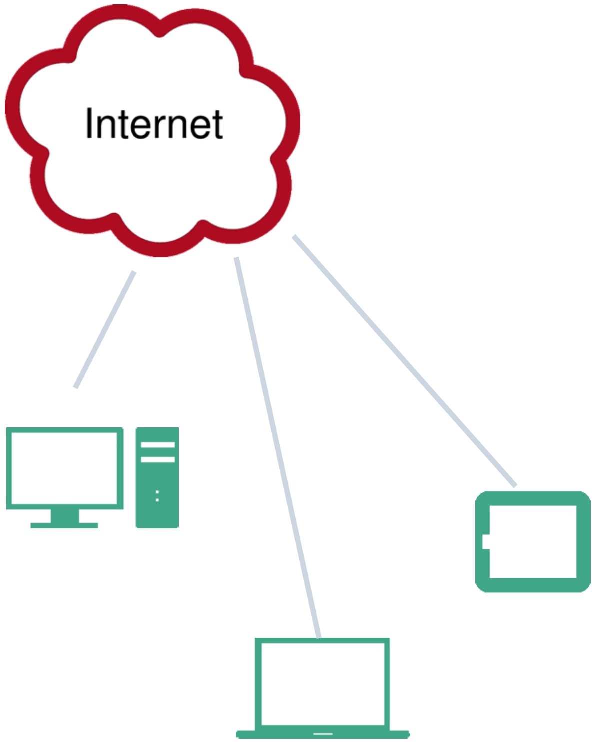
- Open access specs
  - interoperability
- Open source:
  OS + protocol implementations
  - Share dev load, accelerate innovation

The Internet of Things (IoT)

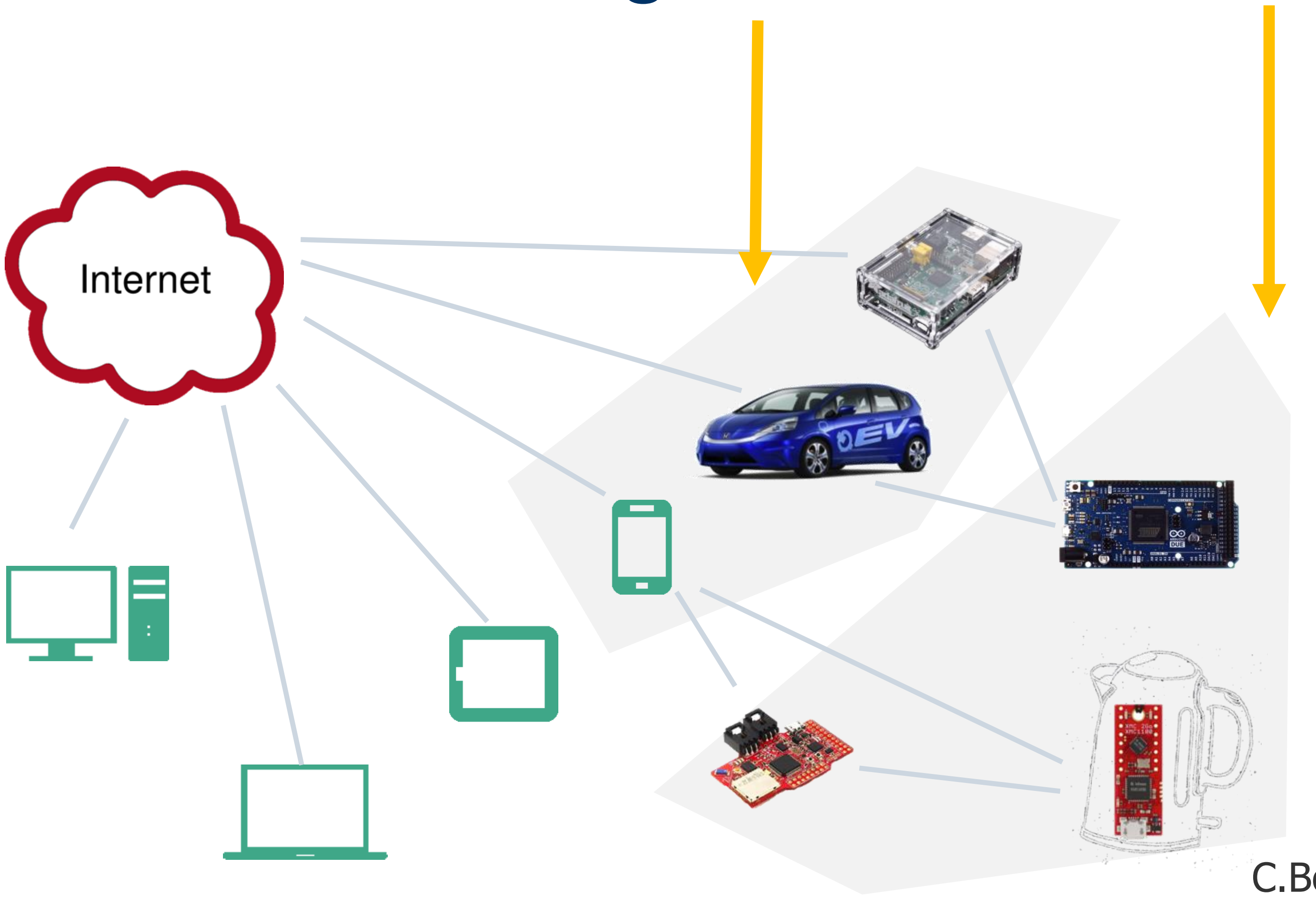


Constrained + Wireless!

IoT Devices:

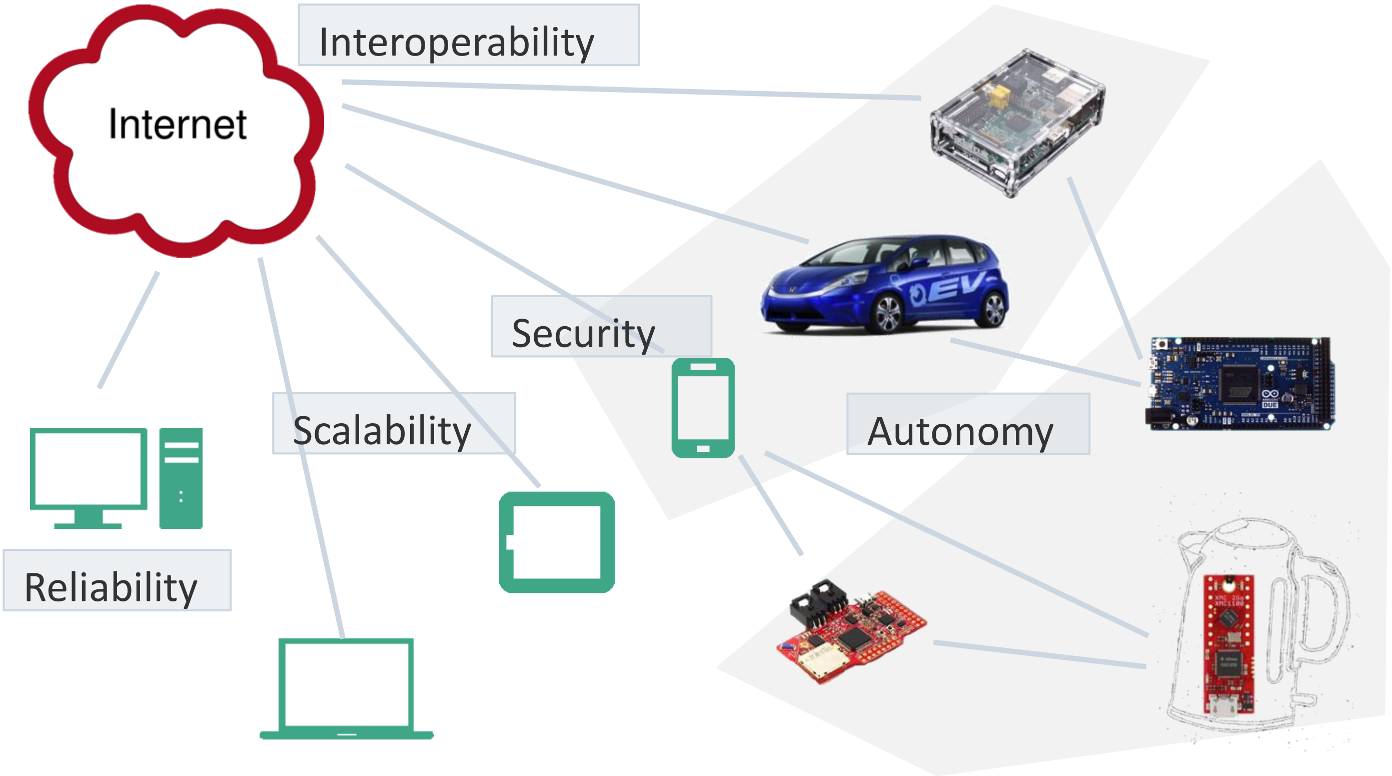


IoT Devices: High-end vs Low-end

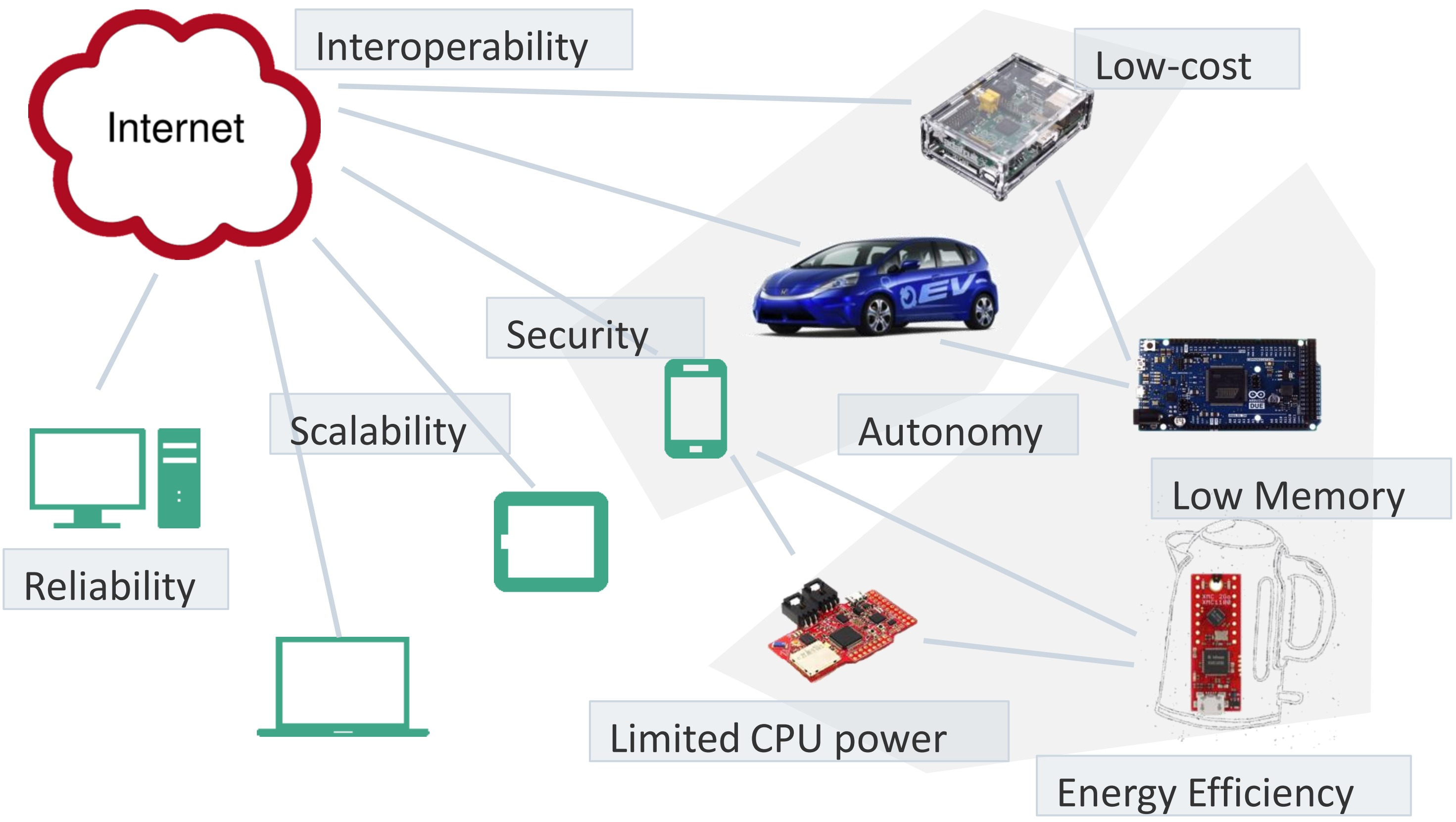


C.Bormann et al. "RFC 7228: Terminology for Constrained-Node Networks," IETF, May 2014.

IoT Requirements



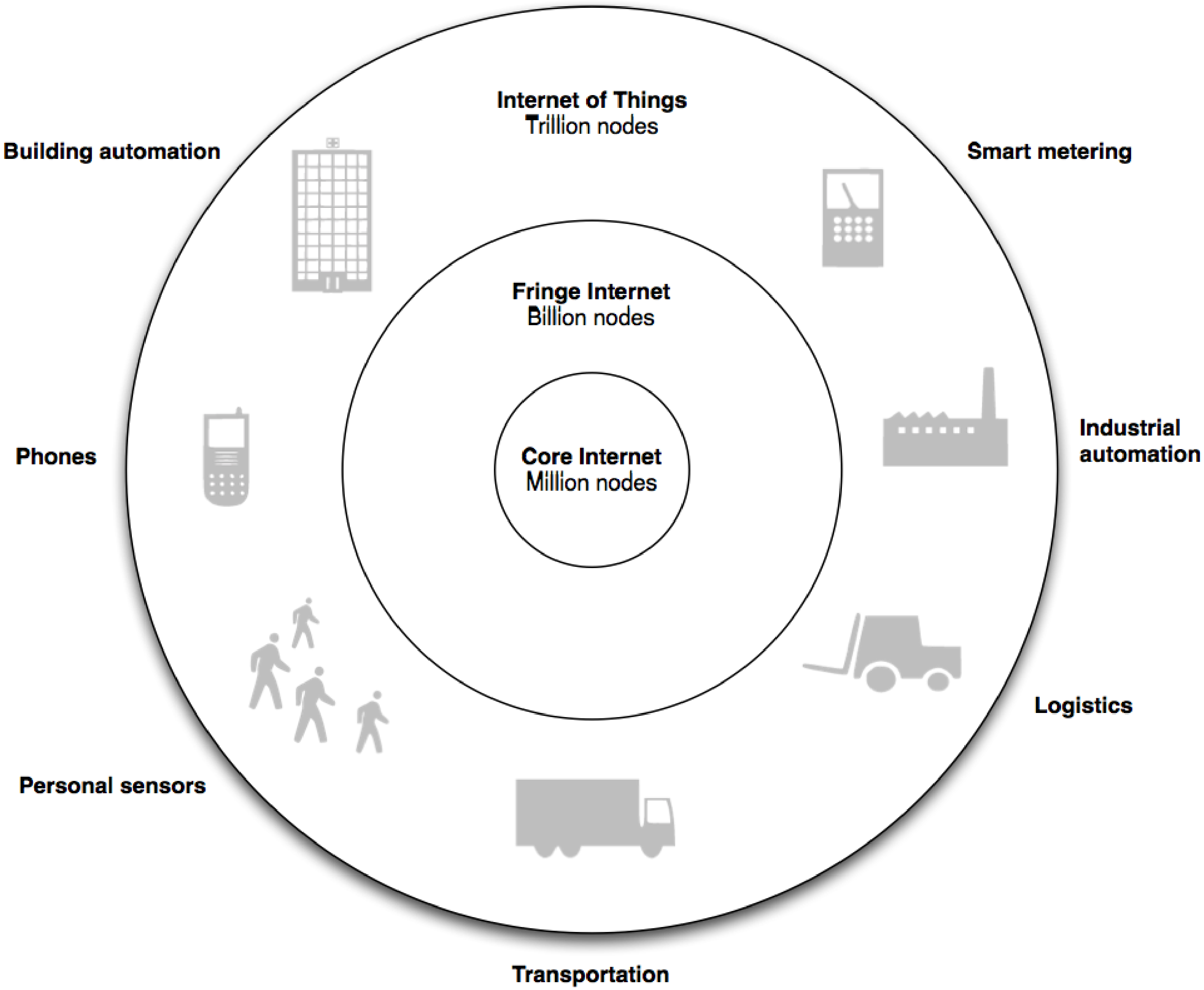
IoT Requirements: Constraints



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


Internet of Things
Trillion nodes
Building automation
Smart metering
Fringe Internet
Billion nodes
Core Internet
Million nodes
Phones
Industrial
automation
Logistics
Personal sensors
Transportation

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

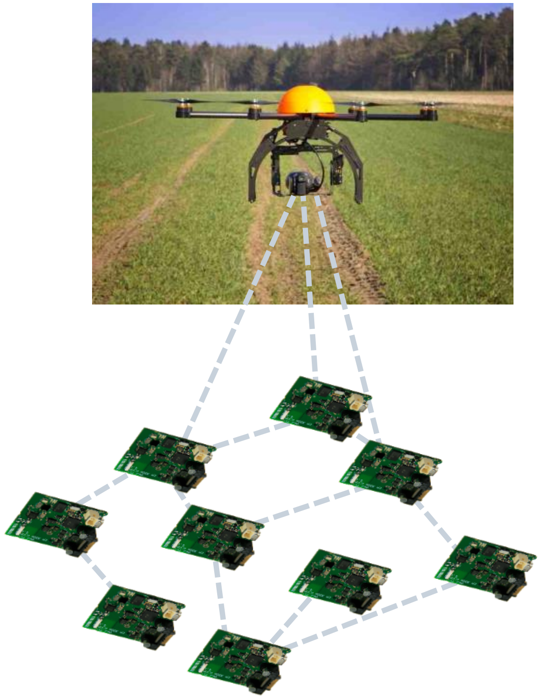
Advanced Metering Infrastructures

Environmental Monitoring

Security and Safety

Industrial Automation

IoT Use Cases



Nature Monitoring

Industry 4.0

Micro Satellites

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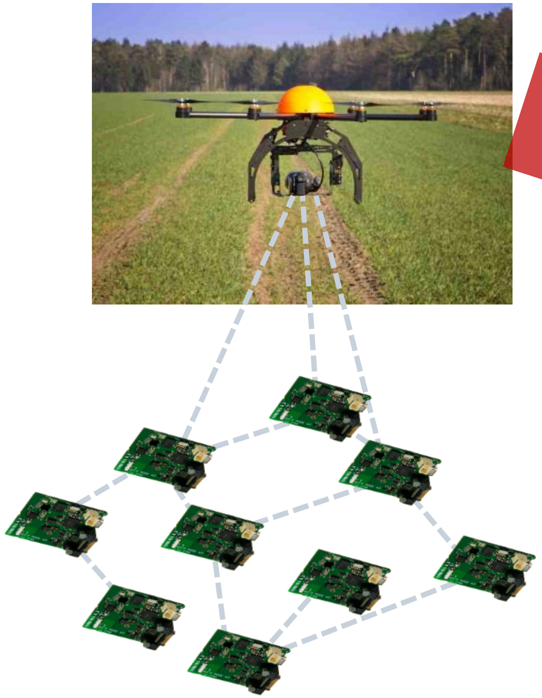
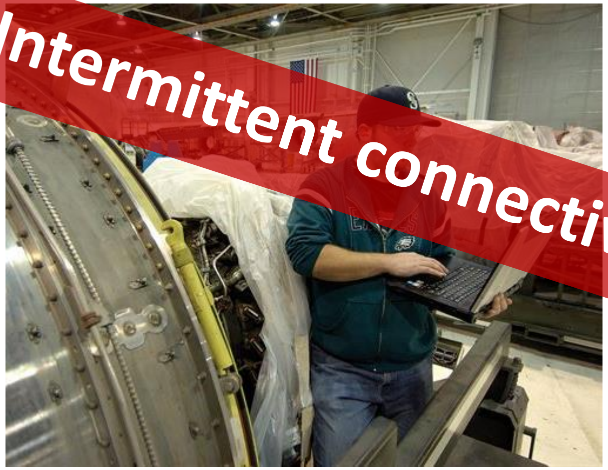
IoT Use Cases

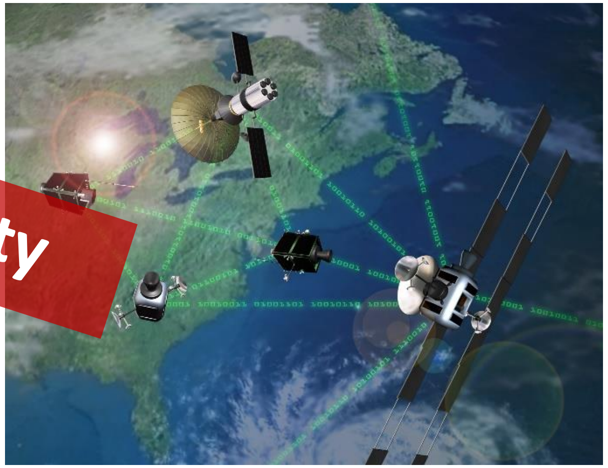
Intermittent connectivity



Nature Monitoring



Industry 4.0



Micro Satellites

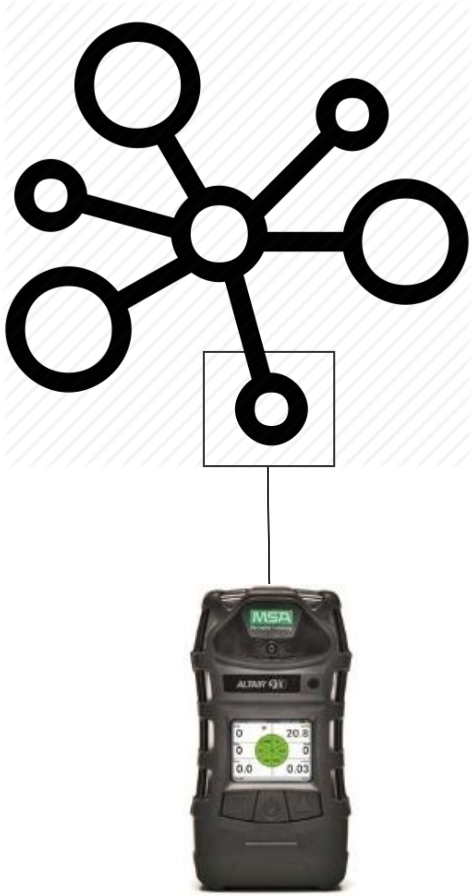
Use Case Safety Monitoring

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

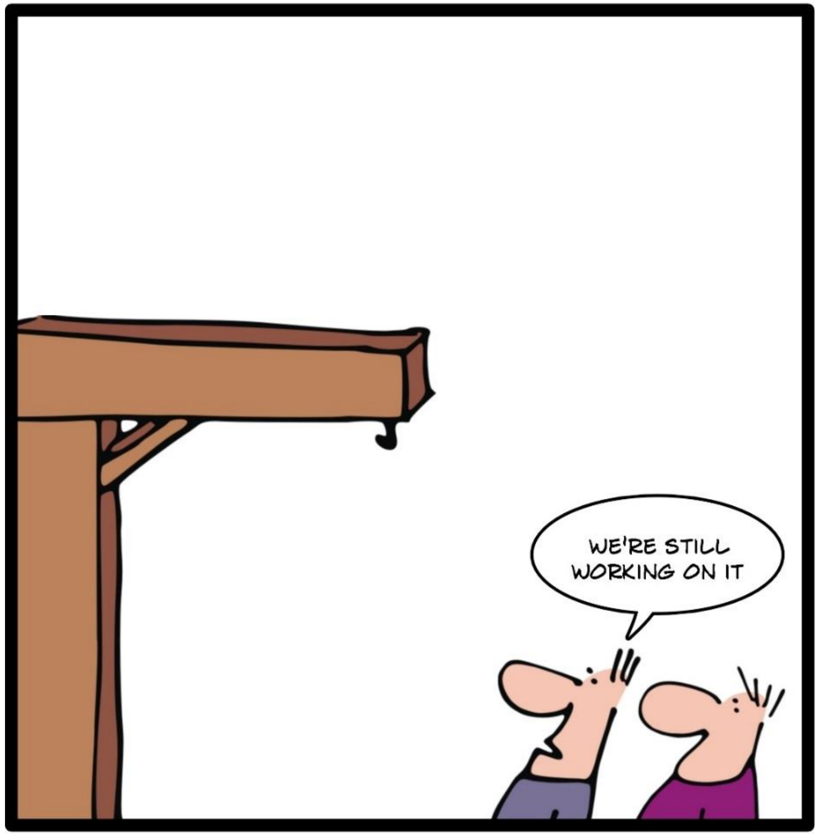
- The Internet of Things
- IoT on Wireless Link Layers
  - Excursion to the World of Wireless
  - Low Power Lossy Links
- IP in the Internet of Things

Mobile Wireless Networks

Two scenarios:

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

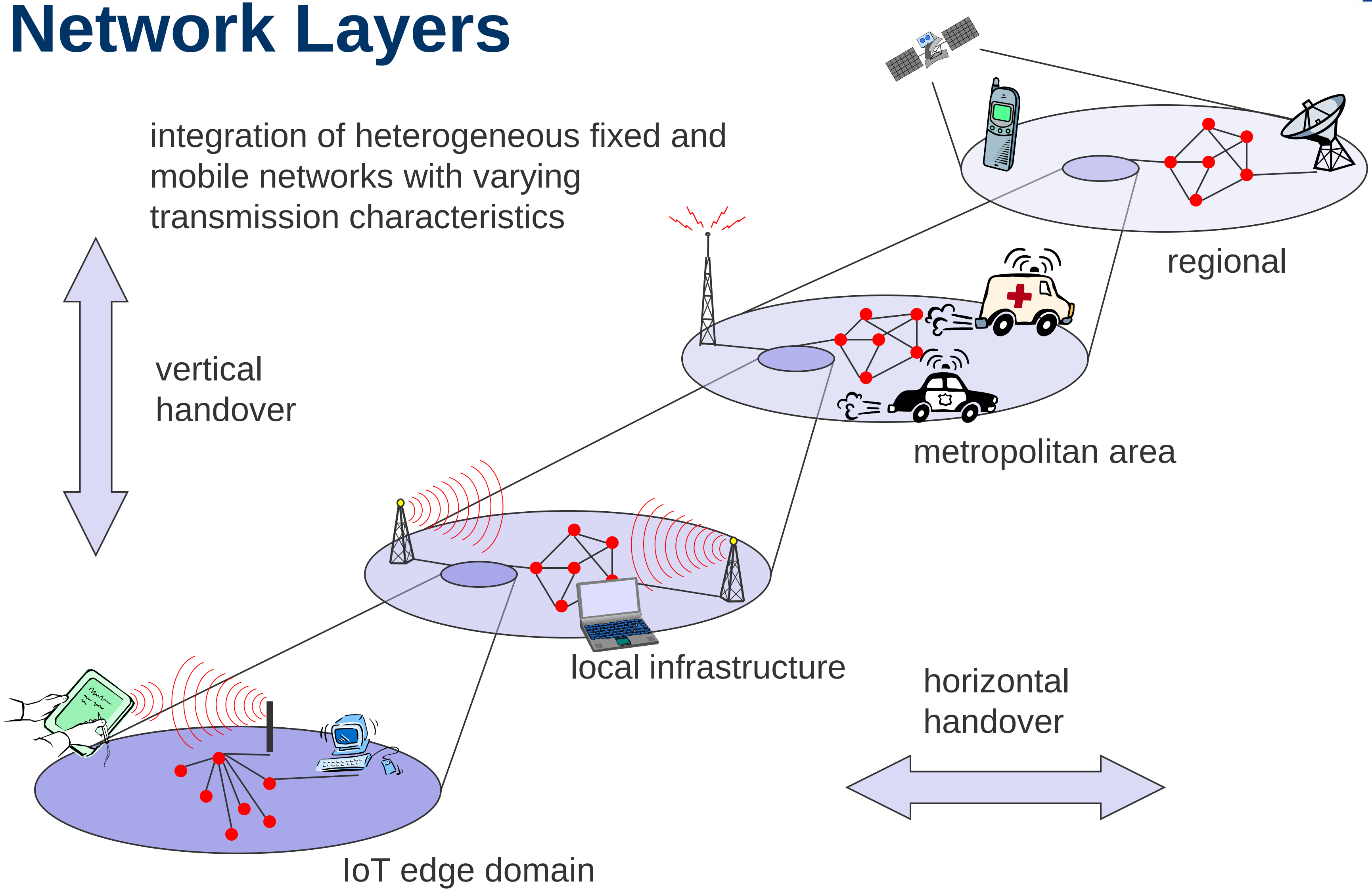
THE HISTORY OF WIRELESS



LONDON 1783:
THE FIRST PROTOTYPE OF THE WIRELESS GALLOWS

The Global View: Overlay Network Layers

integration of heterogeneous fixed and mobile networks with varying transmission characteristics



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

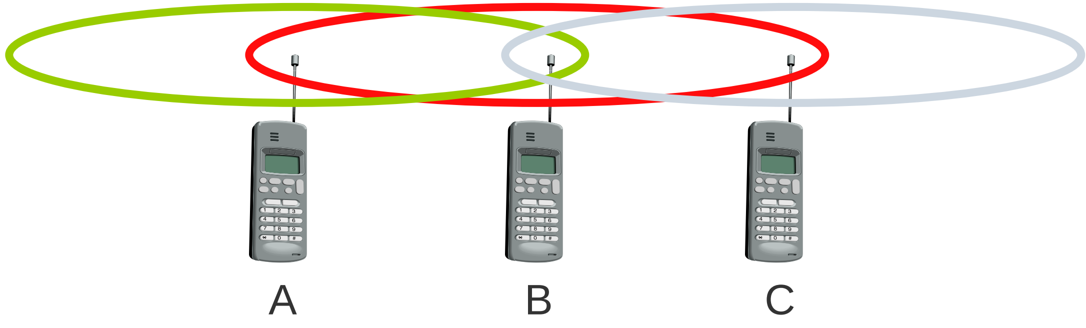
Motivations:

- 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



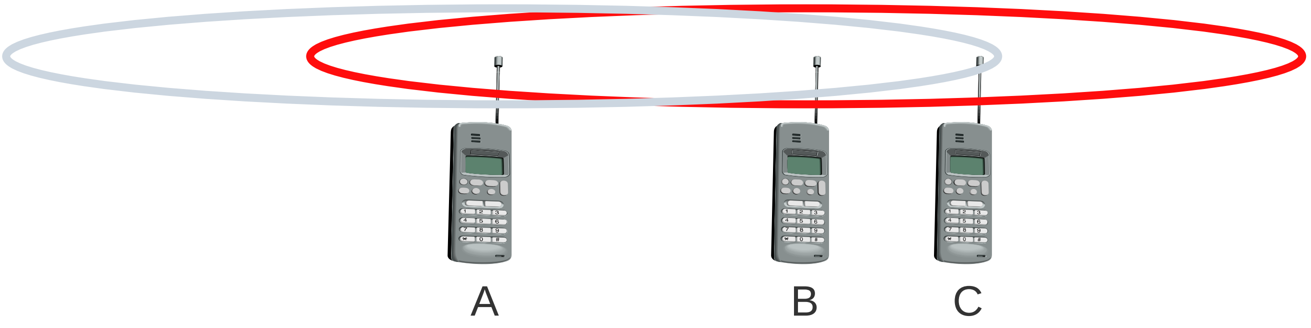
Exposed terminals

- 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

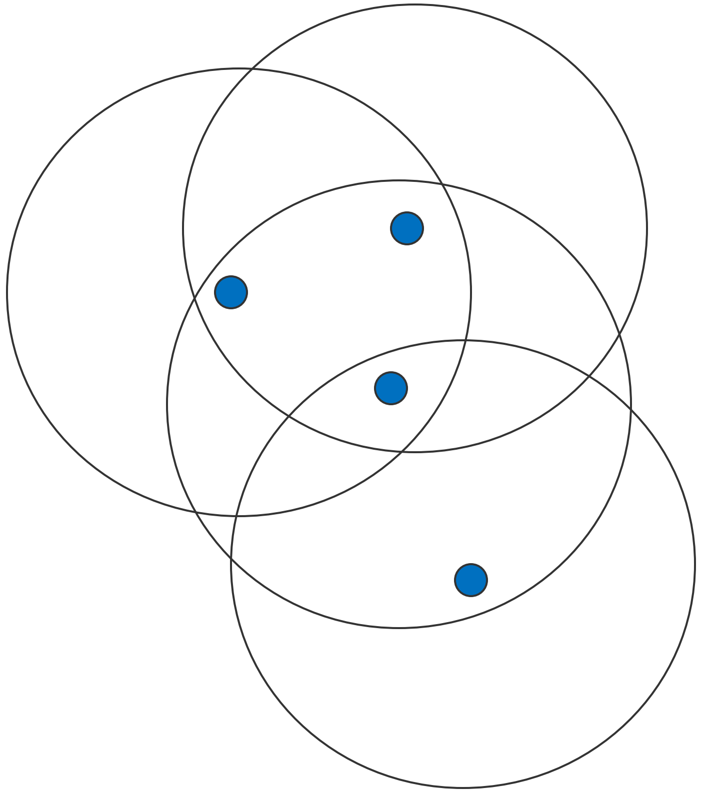


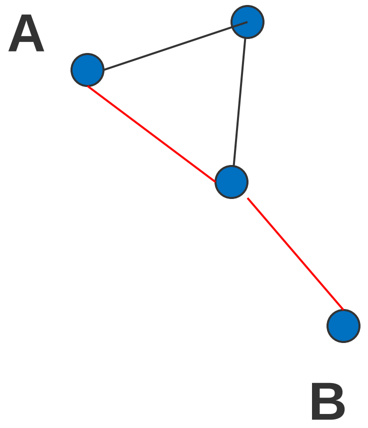
If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer

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

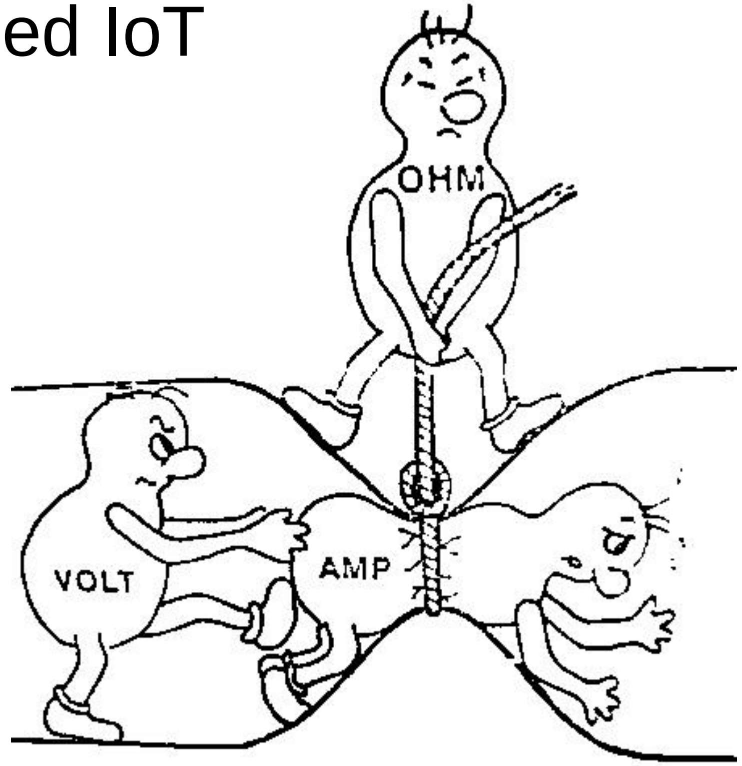
Default networking for the constrained IoT

Typically battery operated

Key problem: energy consumption

Low power leads to loss

Transmission capabilities
are weak



How to Reduce the Radio Energy Consumption?

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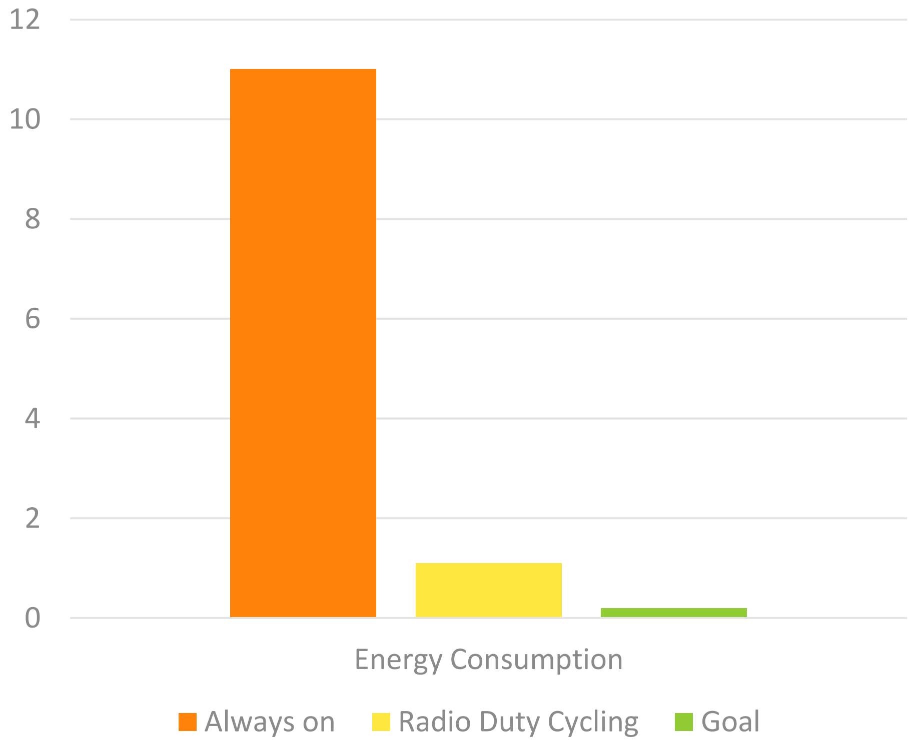


Energy Savings along the IoT Protocol Stack

Protocols		Mechanisms
CoAP	Content Aware	Pre-determined proxy
UDP	Transport	--
RPL	Routing	Reduced state & trickle
IPv6 / 6LoWPAN	Network	Compressed pkt headers
802.15.4, BLE, LoRA…	Medium Access	Minimized idle listening
ISM band	Physical	Low-power radio

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, Sigfox (proprietary)

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

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

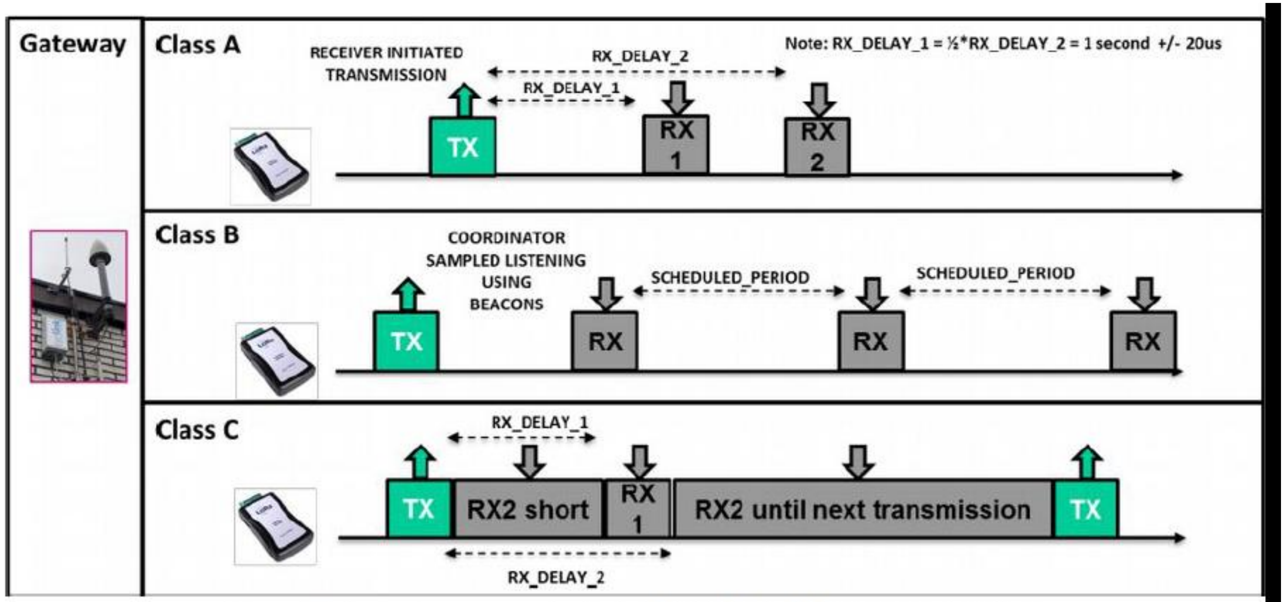
Class B

Receive windows scheduled

Class C

Always listen

Highest power consumption



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

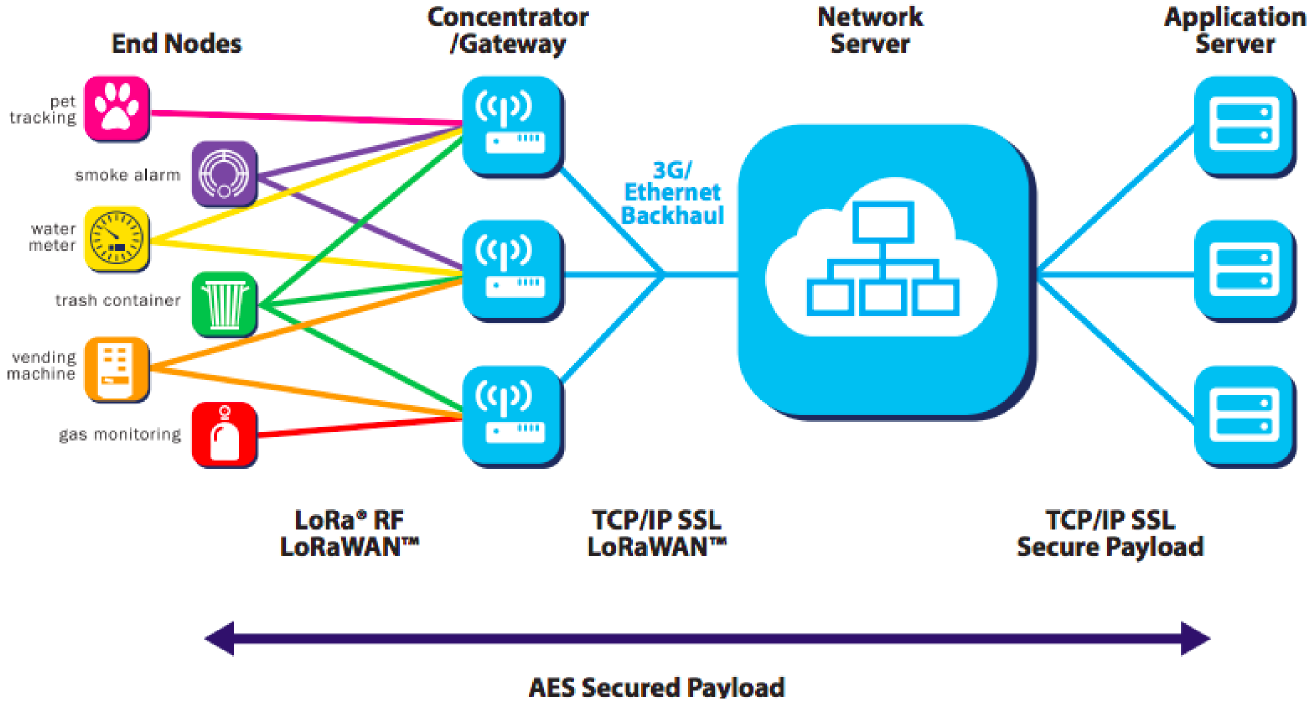
LoRa: IP-Embedding by LoRaWAN

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

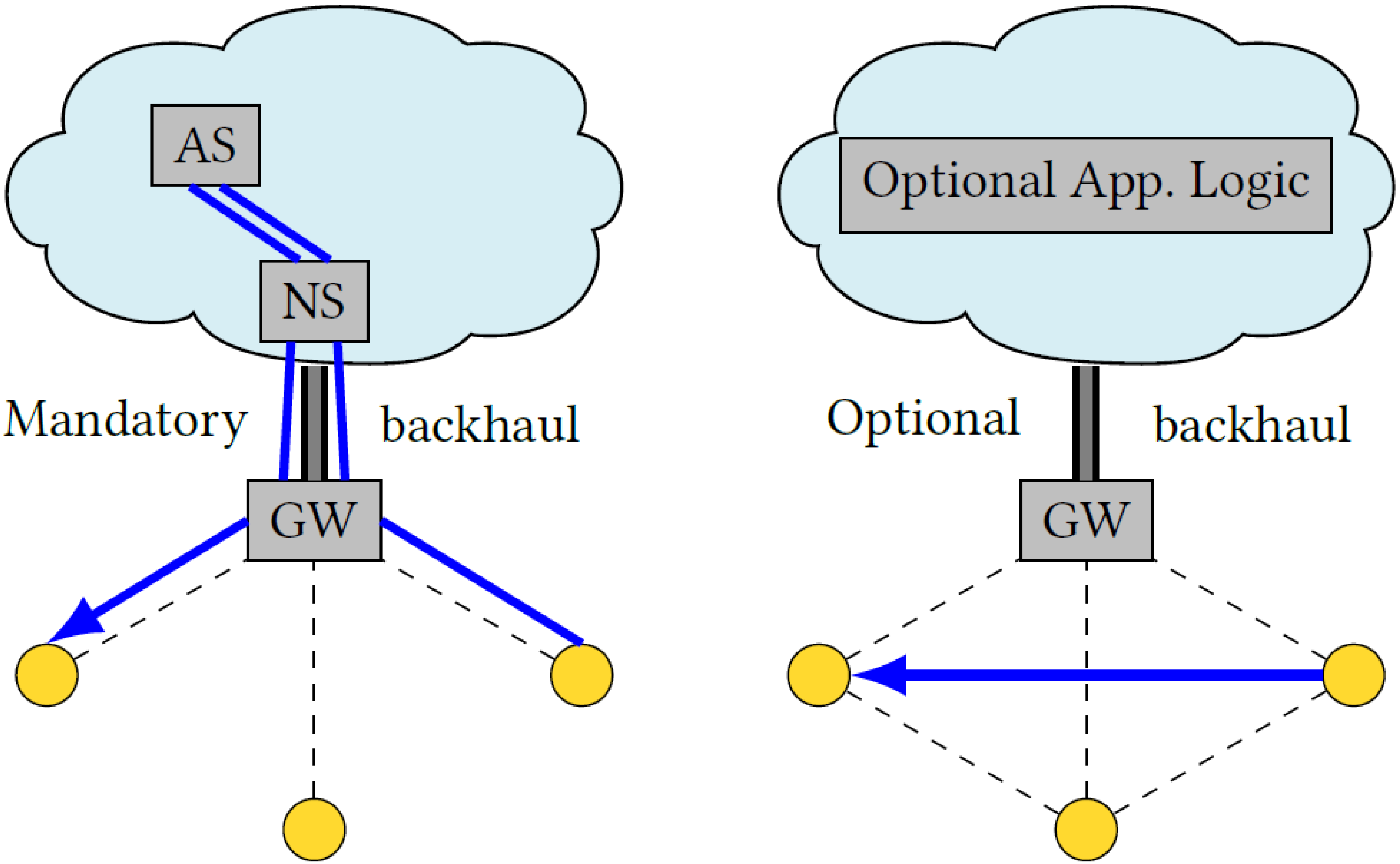
LoRa wireless modulation:

- 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

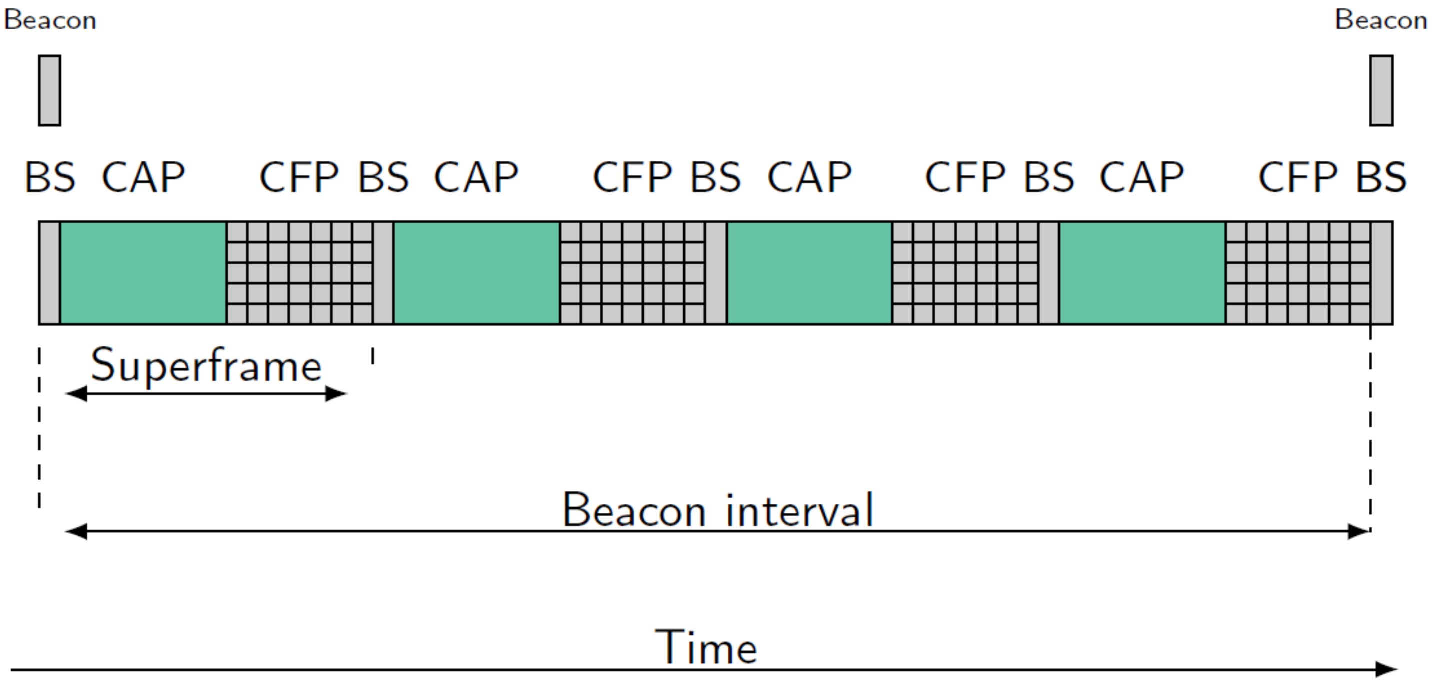
LoRa: Client-to-Client Communication?



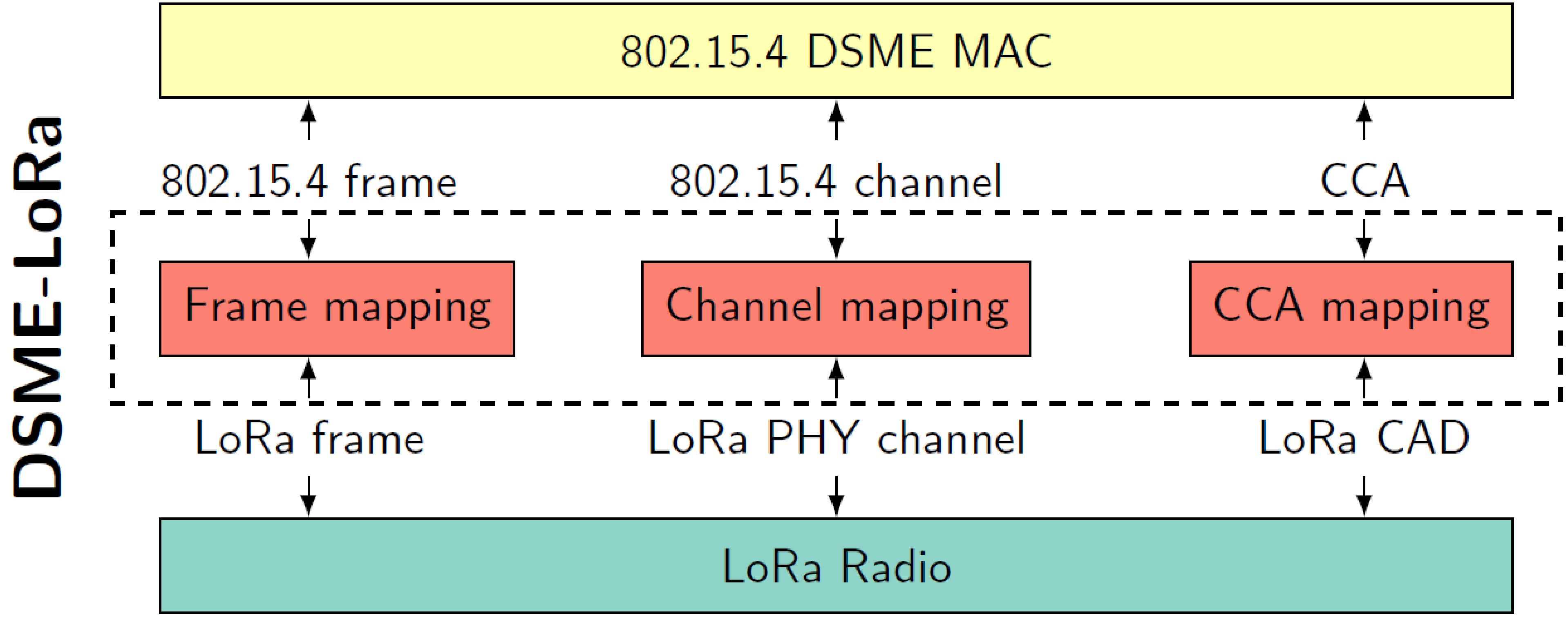
DSME MAC

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

DSME Multiframe Structure



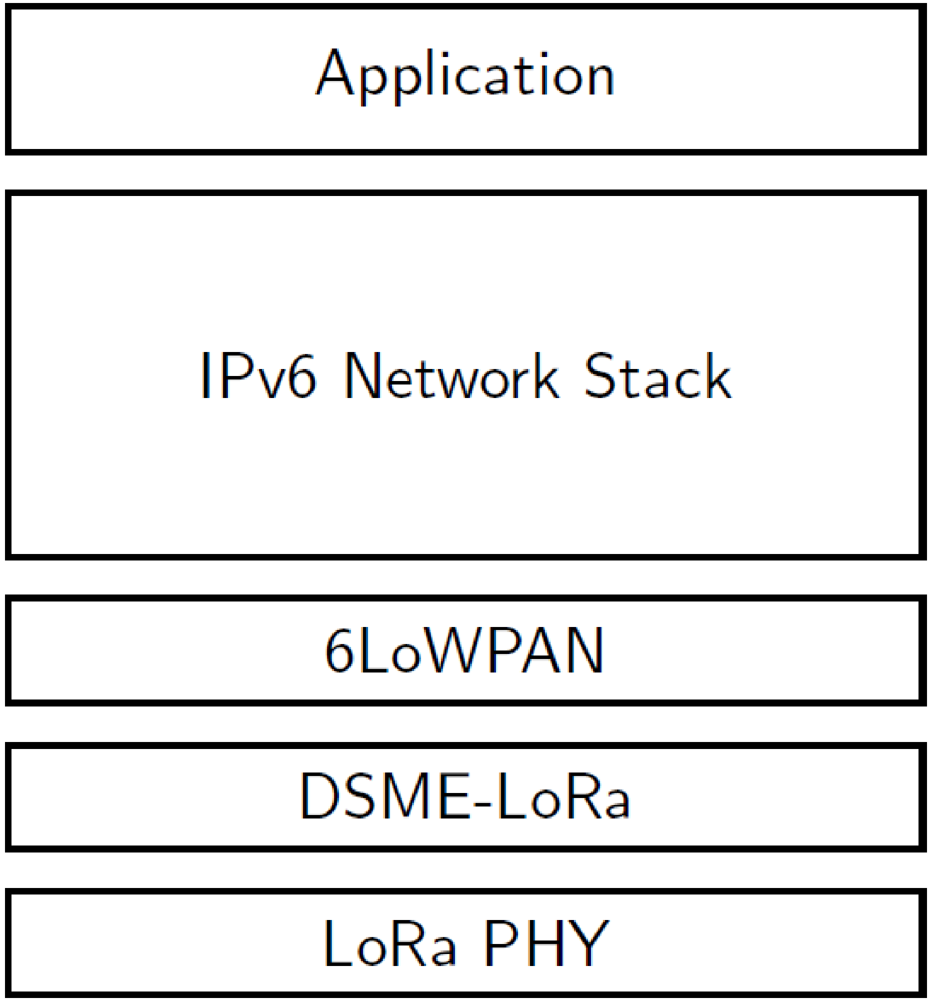
DSME-LoRa


DSME-LoRa
802.15.4 DSME MAC
802.15.4 frame
802.15.4 channel
CCA
Frame mapping
Channel mapping
CCA mapping
LoRa frame
LoRa PHY channel
LoRa CAD
LoRa Radio

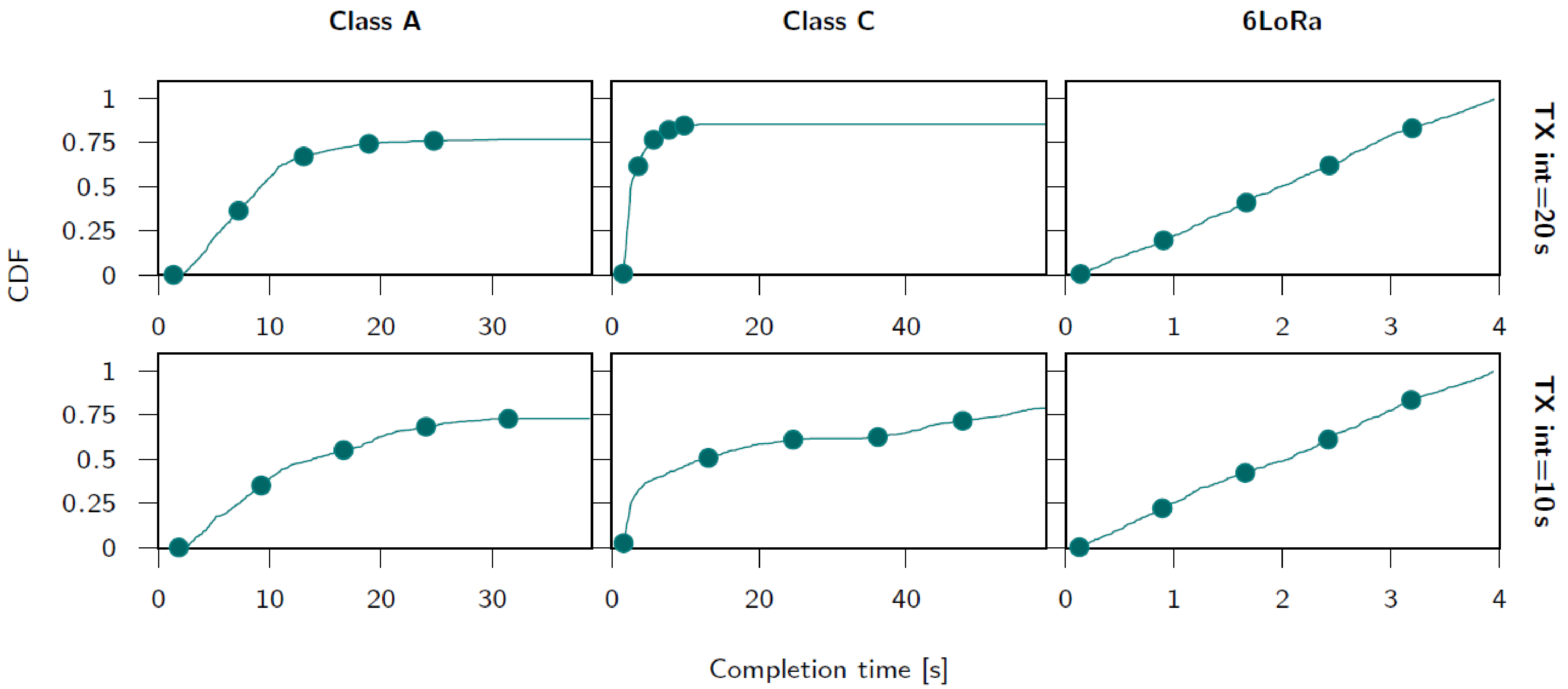
6LoRa: Transmission of IPv6 Packets over LoRa

- IETF 6LoWPAN[a] for IPv6 transmission over IEEE 802.15.4
- Inherit 6LoWPAN roles

[a] RFC 6282. September 2011.



6LoRa Performance: Packet Reception



Energy Consumption

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

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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.

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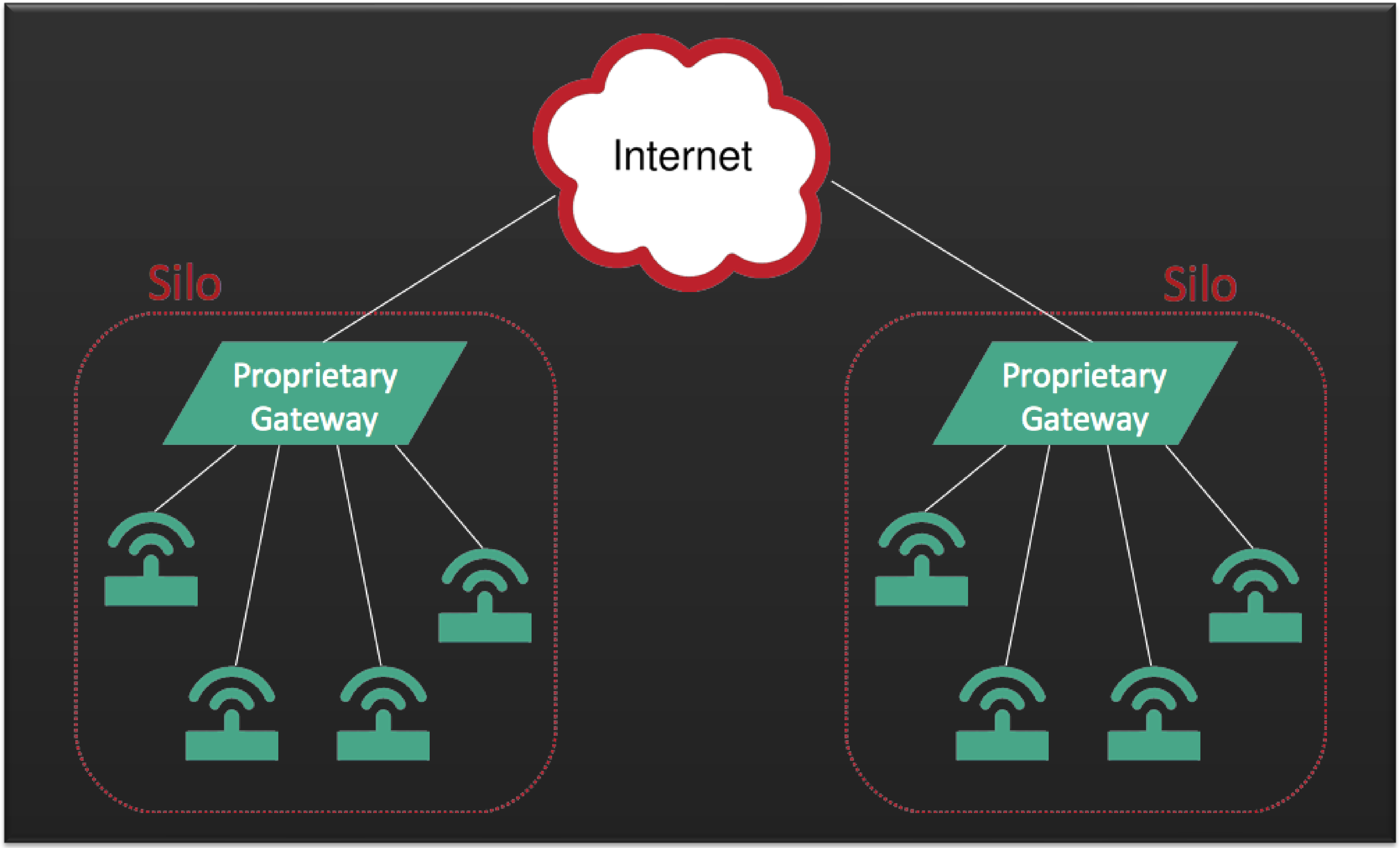
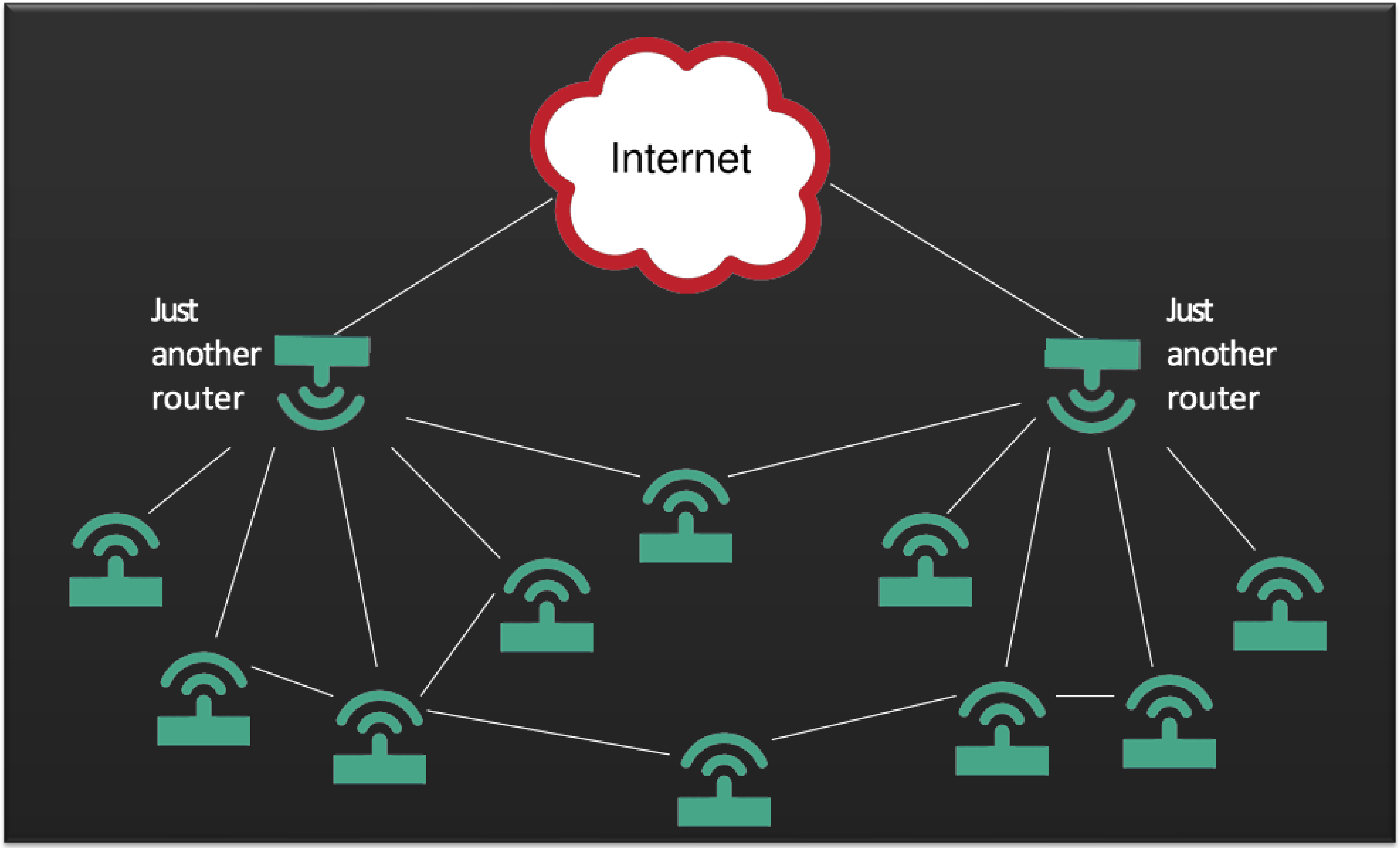
Agenda

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

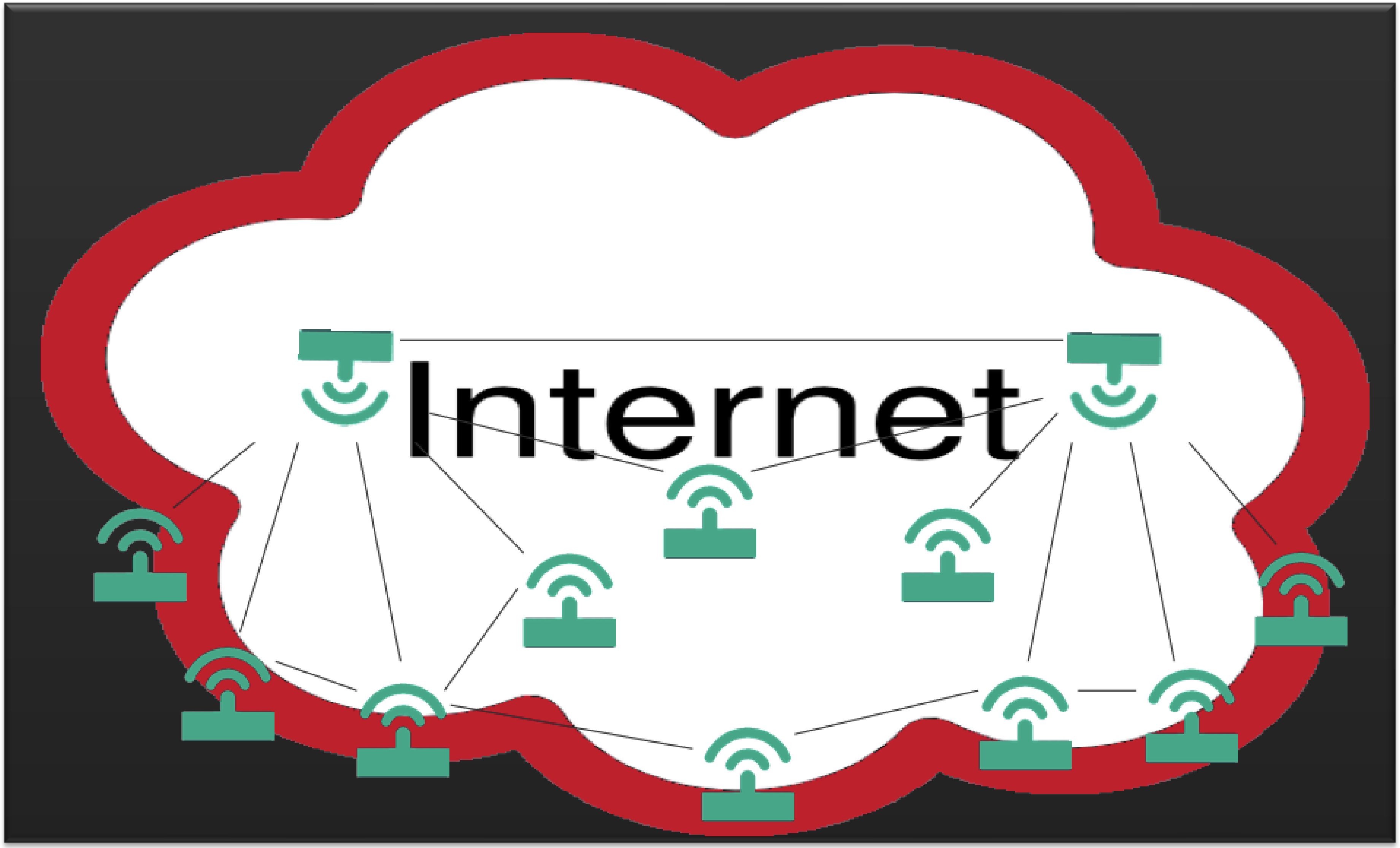
The IoT today looks mostly like this



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 (⊃ 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

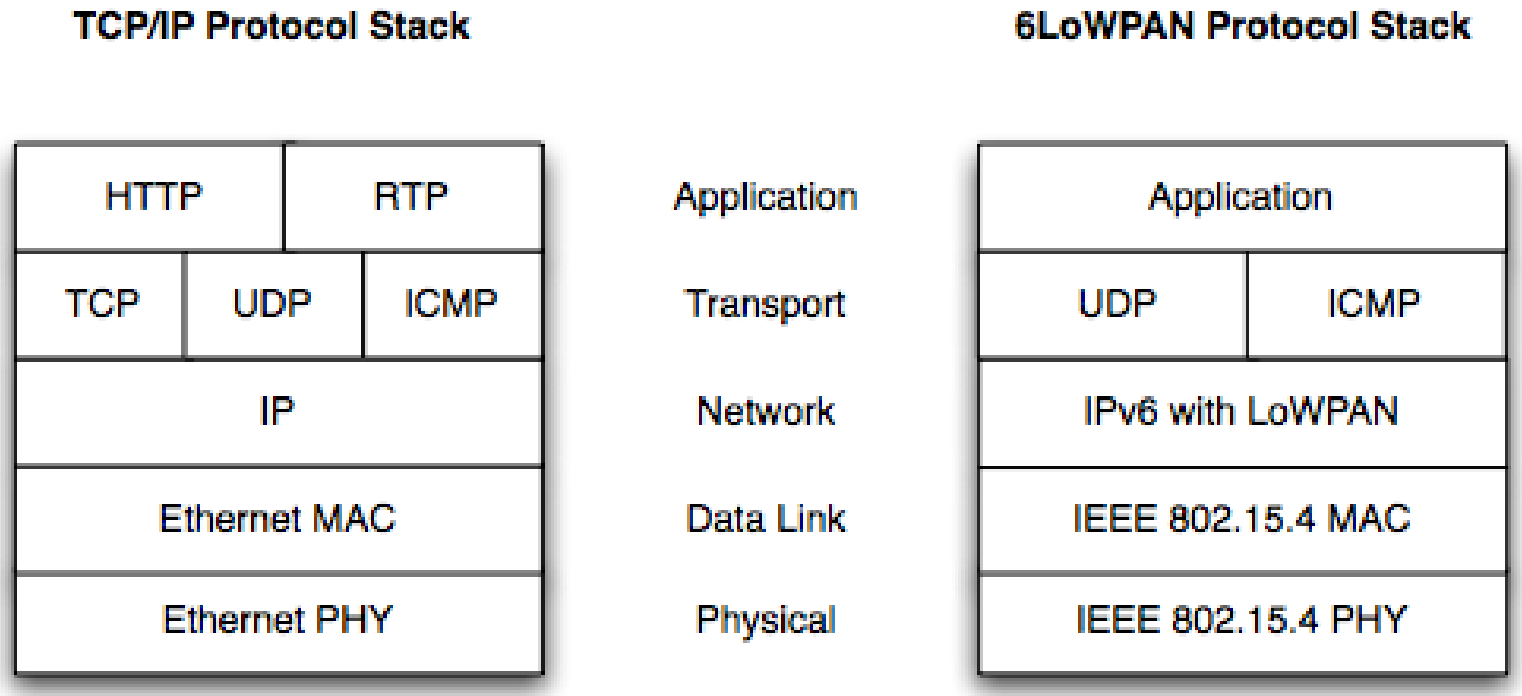
- Stateless and stateful header compression
- Optimized neighbor discovery
- Standard Socket API

Challenges of LoWPAN

Impact Analysis	Addressing	Routing	Security	Network management
Low power (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 (<$10/unit)	Stateless address generation	Small or no routing tables	Ease of Use, simple bootstrapping	Space constraints
Low bandwidth (<300kbps)	Compressed addresses	Low routing overhead	Low packet overhead	Low network overhead
High density (<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

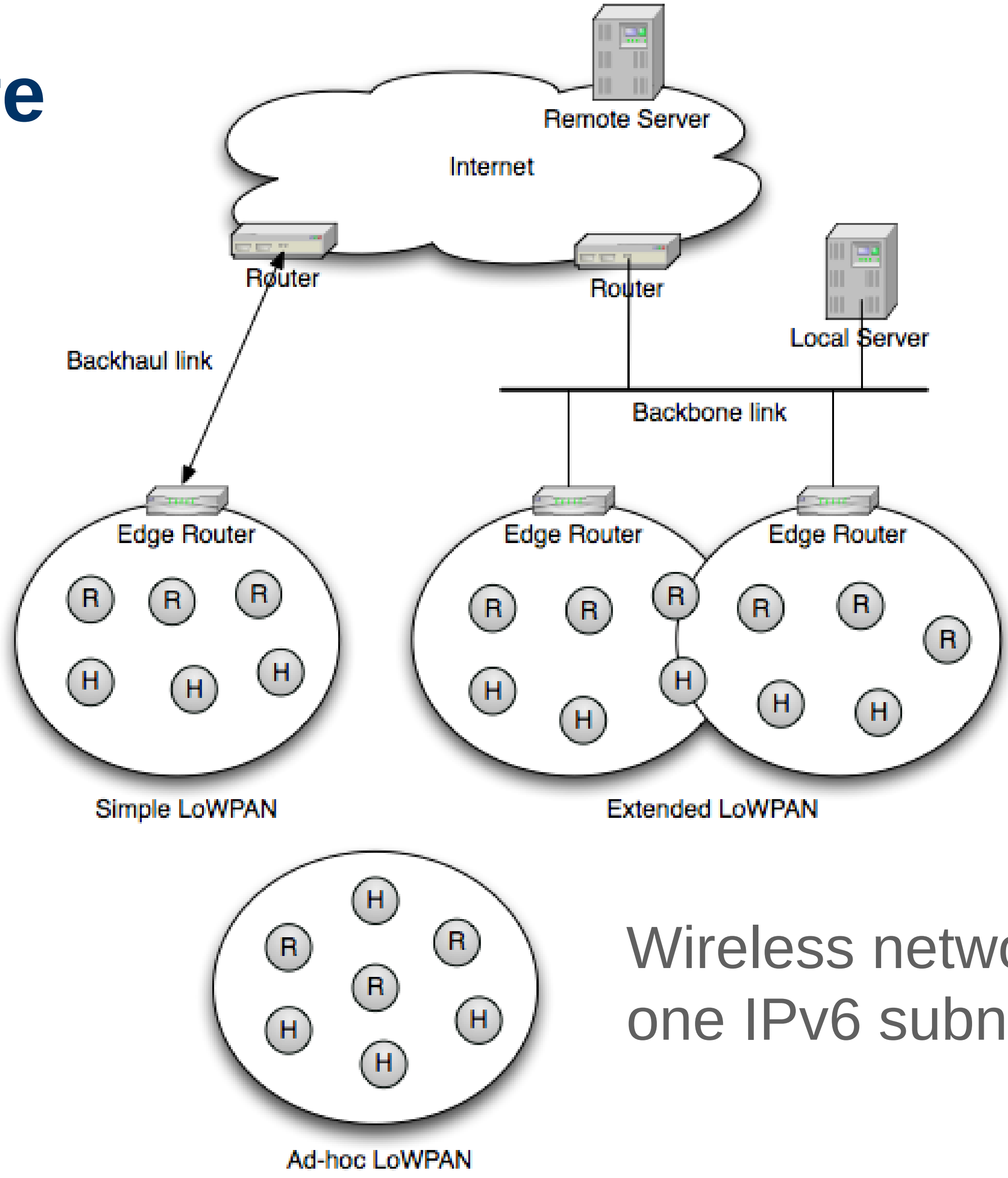
Source: Kushalnagar/Montenegro@IETF62

Protocol Stack



Source: Shelby & Bormann – 6LoWPAN, Wiley 2011

Architecture

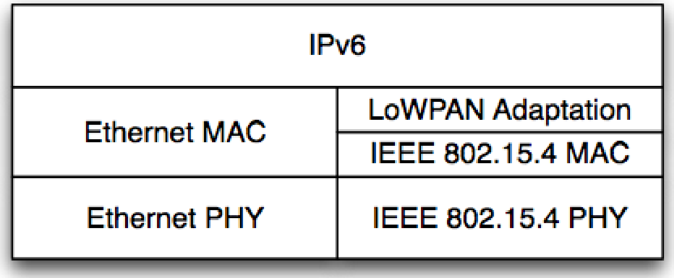


Wireless network is one IPv6 subnet

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-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

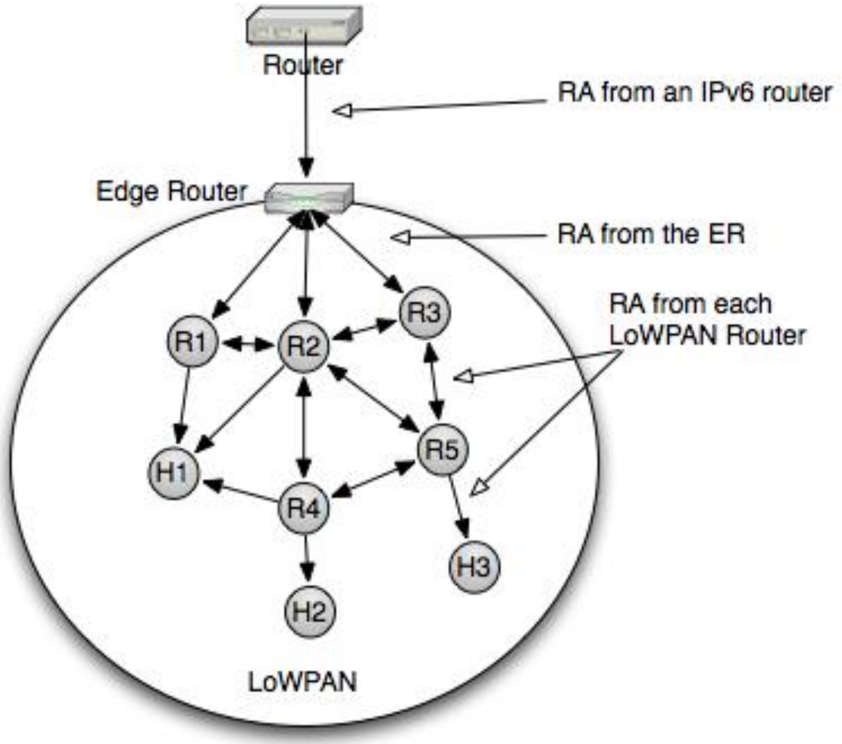
Adaptive Neighbor Discovery RFC 6775

Includes „route-over“ (L3 routing)

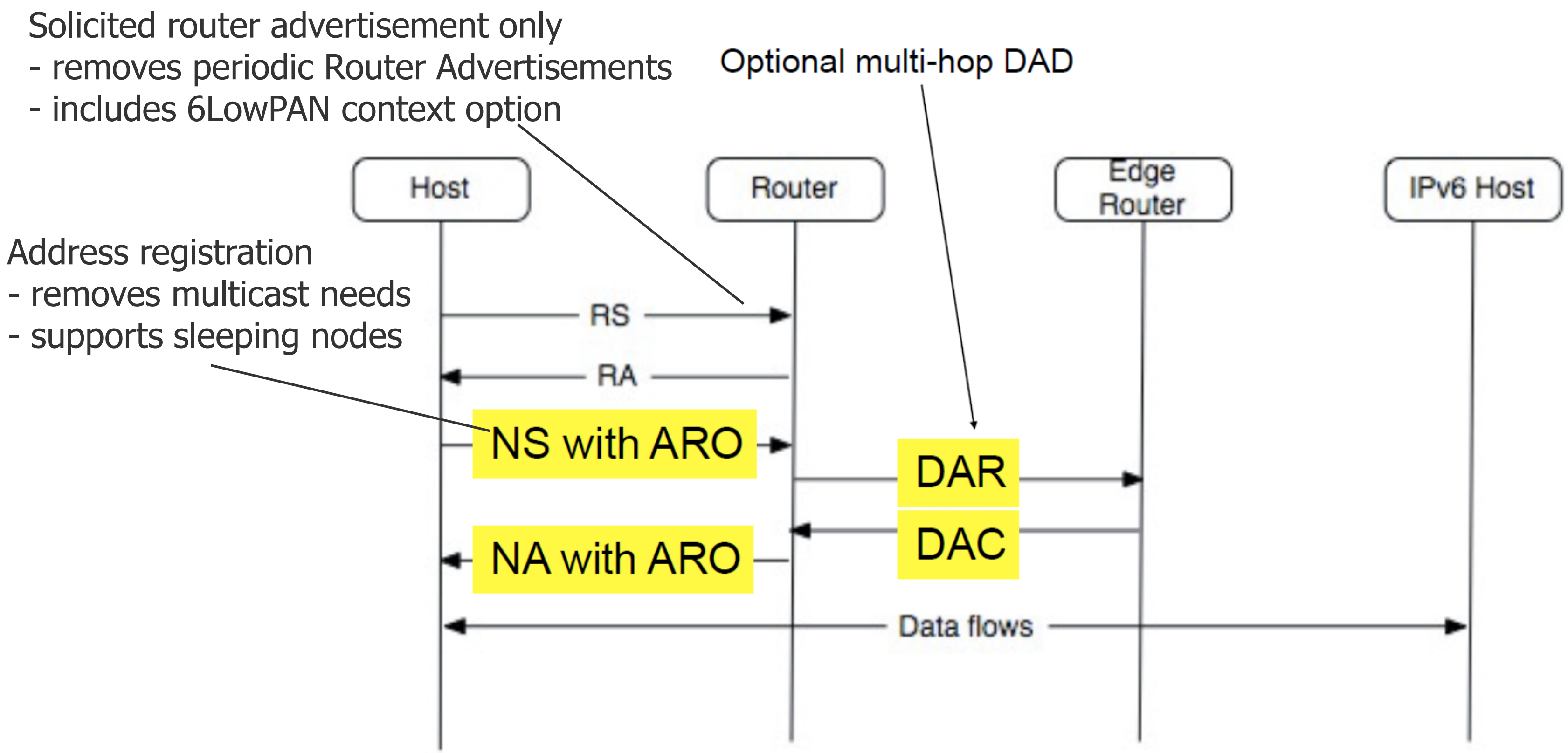
Multihop forwarding of Router Advertisements (GW and prefix dissemination)

Address Registration and Confirmation at Router

Router keeps track of wireless nodes (incl. DAD)



Typical 6LowPAN-ND Exchange



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

LoWPAN IPv6 UDP

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Dispatch with LOWPAN_IPHC   |   LOWPAN_NHC  |  Src  |  Dst  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          UDP Checksum         |          UDP Payload       ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

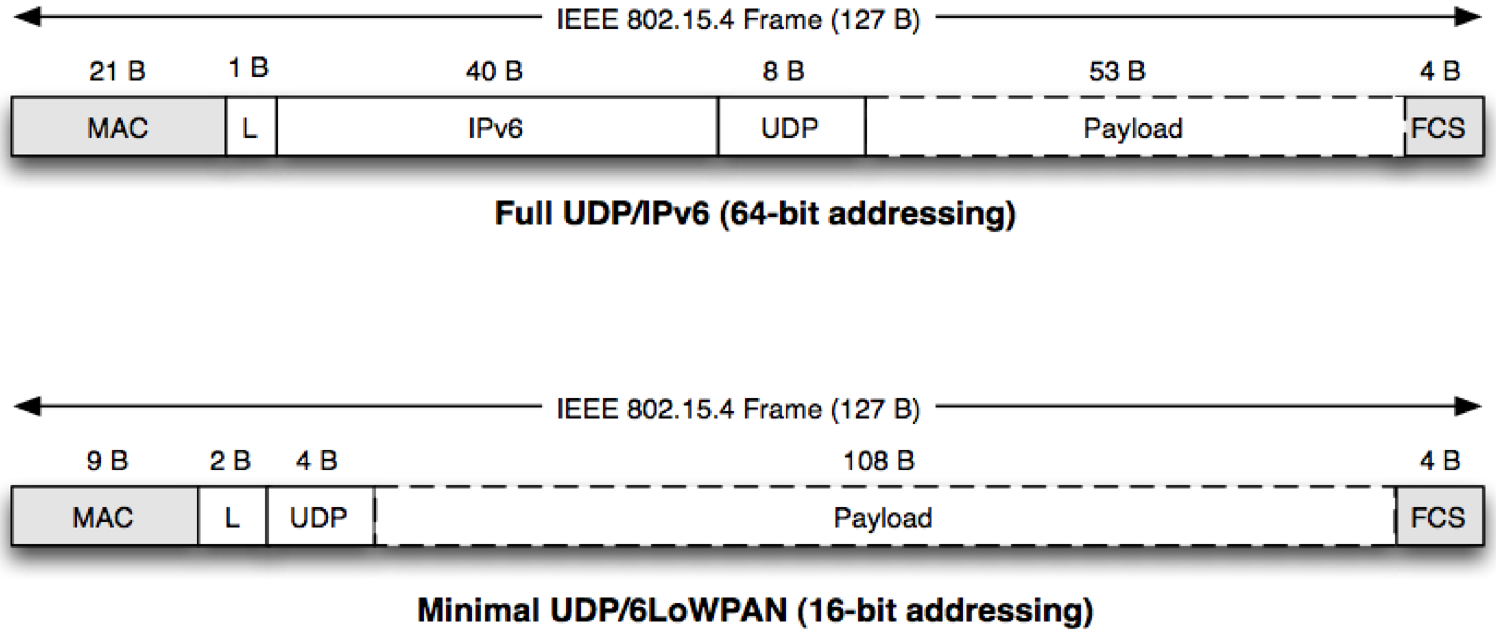
Payload

6 Bytes!

6LoWPAN Headers

Orthogonal header format for efficiency

Stateless header compression



Source: Shelby & Bormann – 6LoWPAN, Wiley 2011

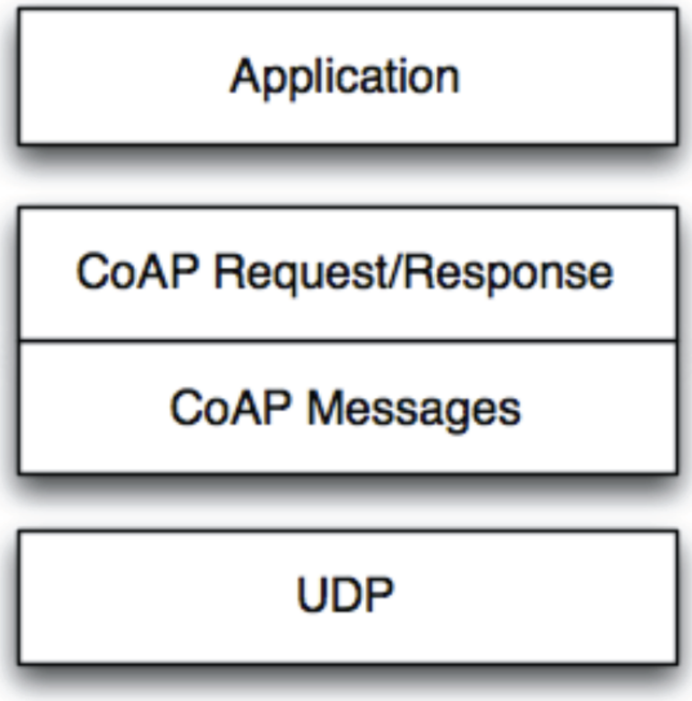
CoAP: Constrained Application Protocol

- 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:

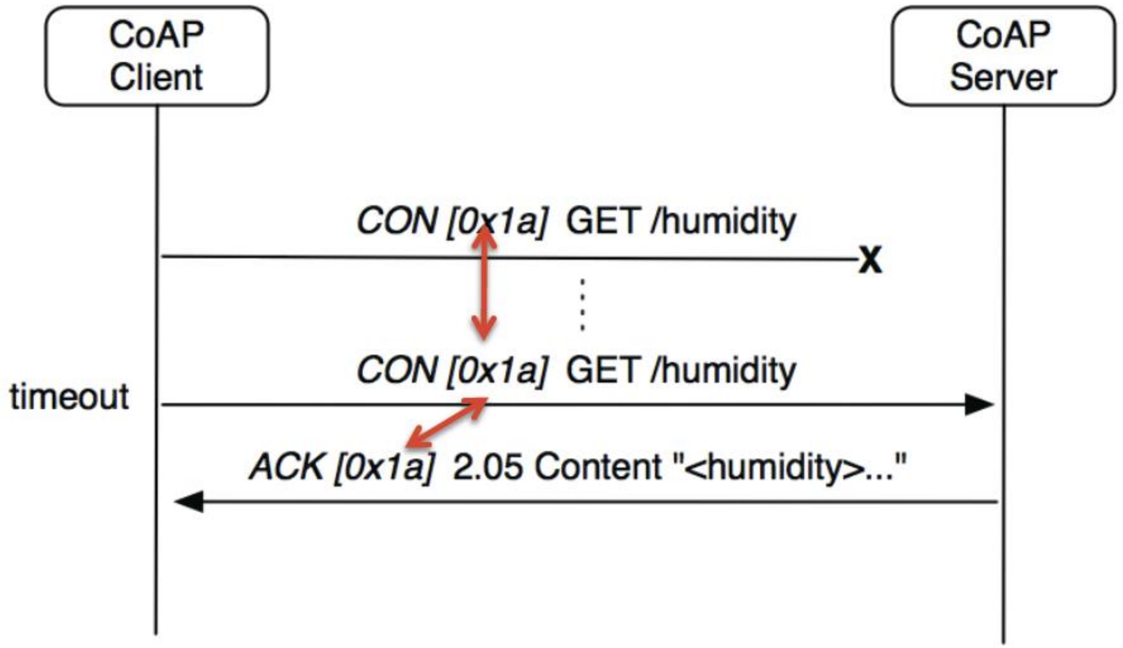
- Confirmable (CON)
- Non-Confirmable (NON)
- Acknowledgement (ACK)
- Un-processing (RST)



REST Request/Response piggybacked on CoAP Messages

Methods: Get, Put, Post, Delete

Message Transactions, Packet Loss

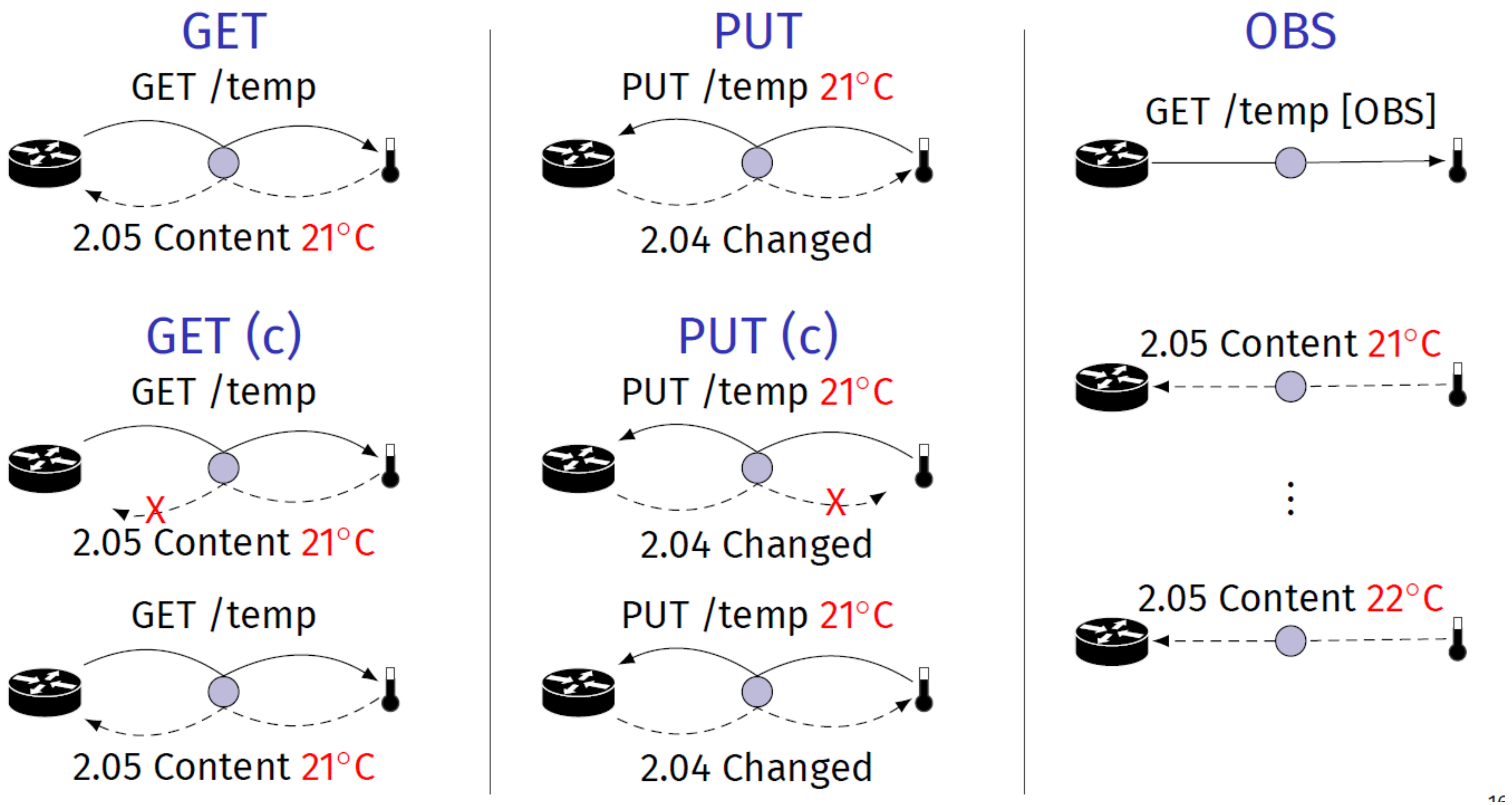


Each message carries an ID (transactional processing) and an optional token (for asynchronous matching)

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

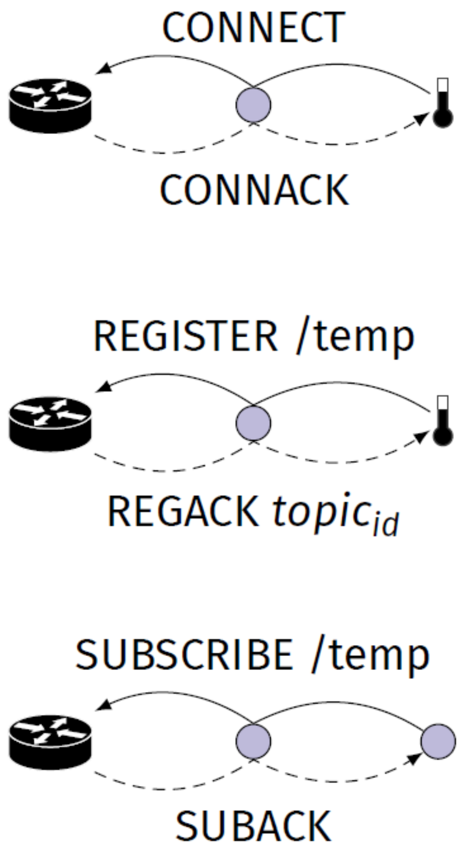
MQTT-SN – UDP-based variant for the IoT

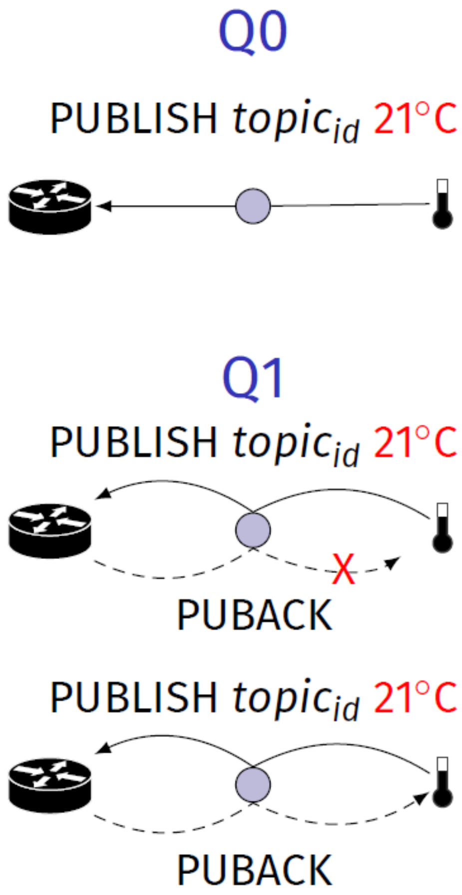
Publishers and subscribers exchange data via a Broker

Different quality levels:

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

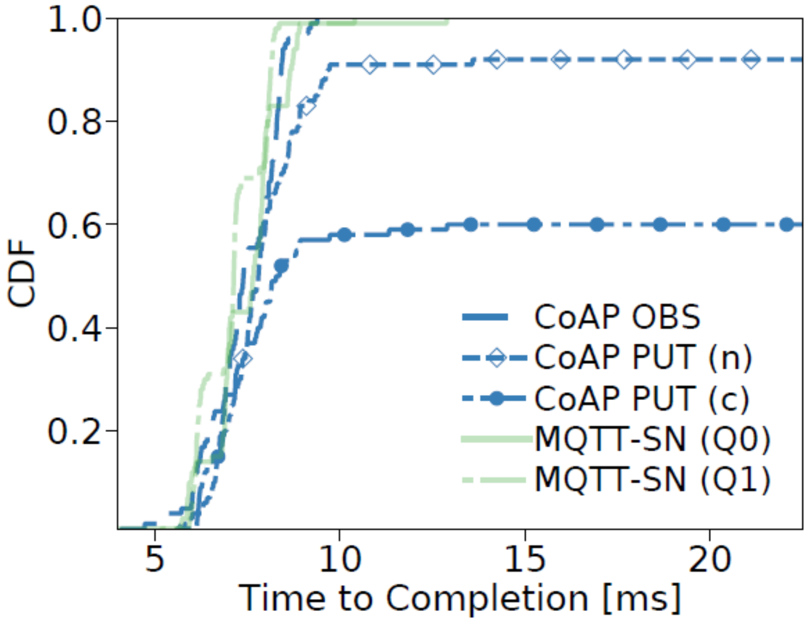
MQTT-SN Operational Modes



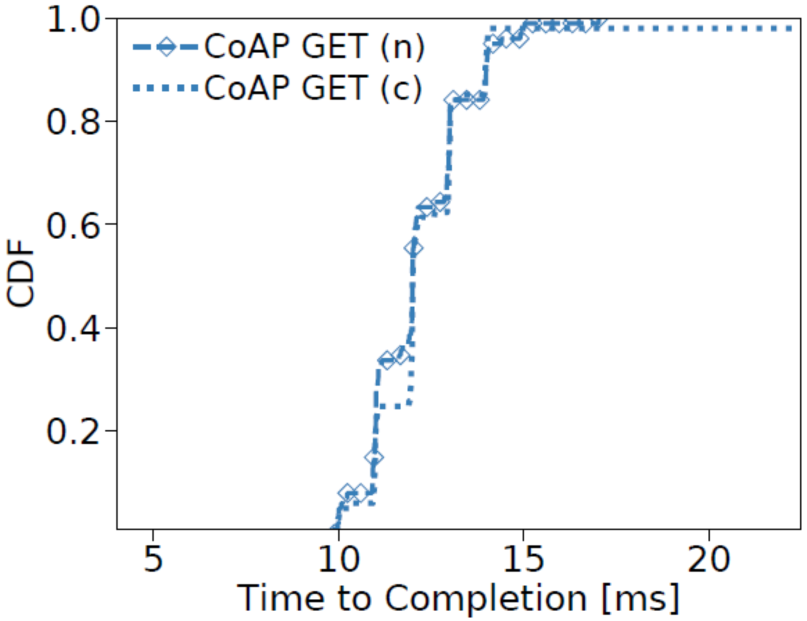


Performance Comparison
Experiments in a Single Hop Testbed

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:

Bibliography

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3. 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.
4. 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.
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