5G Cellular systems

Wireless Systems, a.a. 2014/2015

Un. of Rome "La Sapienza"

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5G vision

- 2014 technologies: Connectivity at High Speed + Cheap high computing power (over the Cloud, and at the edges of the network ← fog/edge computing technologies)
- Mobile access does not meet the required QoS
  - achievable coverage, data rates, latency, reliability, energy consumption
- Strong need for next generation ubiquitous ultra-high broadband mobile computing infrastructure

  → 5G under discussion ← many paradigms shifts to overcome current barriers in terms of performance and scalability

  → Objective: provide delay critical, ultra reliable, dependable secure broaband communications services to mobile users

  → not only to humans but also to tens of bilions of smart objects, cyber physical systems (e.g., cars, robots, drones) that are being deployed as part of the Internet of Things emerging paradigm

5G vision

- Convergence of different wireless systems
  - Vision: moving away from one architecture fits all towards a "Multiple architectures adapted to each service" concept
    - ✓ LTE, 3G, 2G, WiFi and satellite networks should cooperate and interwork seamlessy
    - ✓ Multi technology (different phy but also different kinds of network)
  - 5G pan european research infrastructures
  - Security, privacy and IoT support some of the key aspects of the vision
  - To change user experience disruptive change in performance & system optimization; service support; change in business models
    - →Examples: extension of usable bandwidth; Reduction of cost per bit; Programmable network; Low energy consumption & long lifetimes (also through harvesting); Security by design,…

5G KPIs

- Throughput: provide 1000x more available throughput in aggregate, as well as 10x more speed to individual end users (full immersive experience)
- Latency: down to 1ms when needed for tactile Internet
- Energy efficiency: 5% of global energy consumption is due to ICT
  - 90% increase in energy efficiency
  - 1000x improvement in energy efficiency; 10x better battery lifetime for low power devices
- Coverage (really everywhere everytime: from planes, to trains etc.)
- Novel business models (service based)+ reduction of service creation times

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System level challenges

- Privacy by design
- Quality of Service/Quality of Experience challenge: differentiated services across various dimensions (throughput, latency, resilience, costs but also security, availability, resilience)
- Simplicity challenge (seamless service provisioning even for inter RAT switching)
- Multi-tenancy challenge: provide services across different infrastructure ownership, with different networks coexisting and providing an integrated efficient interaction between mobile systems and the backhaul
- Density challenge (e.g., brought in by IoT devices)

System level challenges

- Diversity challenge
  - must support the increasing diversity of optimized wireless solutions, the diversity in traffic types and number of connected devices
- Harnessing challenge: exploit any communication capability, including device to device for optimizing communication at each time
- Harvesting challenge: exploit energy harvesting to improve lifetime
- Mobility challenge: seamless mobility across networks/ technologies
- Location and context information challenge: submeter localization accuracy
- Hardening challenge: making communication system robust to attacks and natural disasters

System level challenges

- Resource management challenge
  - provide access agnostic control, policy and charging mechanisms and protocols for dynamic establishment, configuration, reconfiguration and release of any type of resource (bandwidth, computation, memory, storage) for any type of device and service.
- Flexibility challenge: device truly flexible control mechanisms and protocols for relocating functions, protocol entities an states relying on technologies such as SDN and NFV
- Identity challenge: provide identity management for any type of device with access agnostic authentication mechanisms
- Manageability: improve menageability of networks (reducing human intervention)

Flexibility, programmability, openness

5G Areas some examples

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-**Cognitive access**, frequency agile

-Large bandwidth (**mmwave comm.**)

-Novel air interfaces

-Different communication

models (unicast/multicast/

Broadcast/**D2D**),

-Exploiting social knowledge

for opportunistic access

IoT Support

Extensive reprogrammability & reconfigurability

System optimization and adaptive

cognitive operation based on context

Use of data analytics, **NVF and SDN**

Harmonization of processes

(Wireless/wired technologies)

Authentication/authorization

QoS

Network view

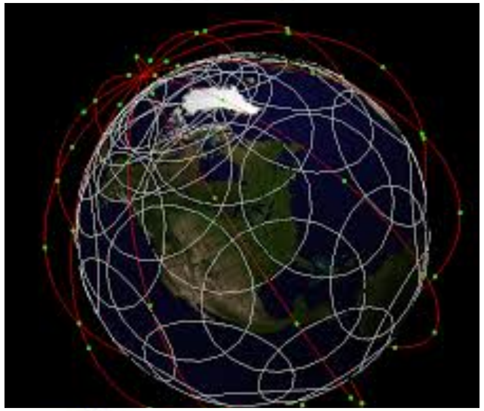
The role of satellite comm.

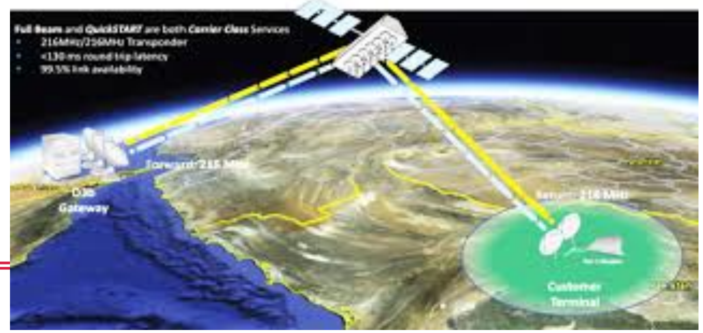
Objectives

- 1Gbps download → 100 Gbps download
- Video broadcasting
- Disaster recovery

Latencies

- 0.12s latency←GEO← 35,000Km
- CommStellation LEO satellites
  - (1000Km)←7ms latency
  - High data rate ←1.2Gbs
  - 78 satellites
  - expected deployment: 2015





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From Internet to Internet of Things

- ✓ Success of Internet → over one billion user;
- ✓ Open standards, evolution with technology needs.

- ✓ Smart objects connected to the Internet
- ✓ 50 billion devices expected to be connected by 2020

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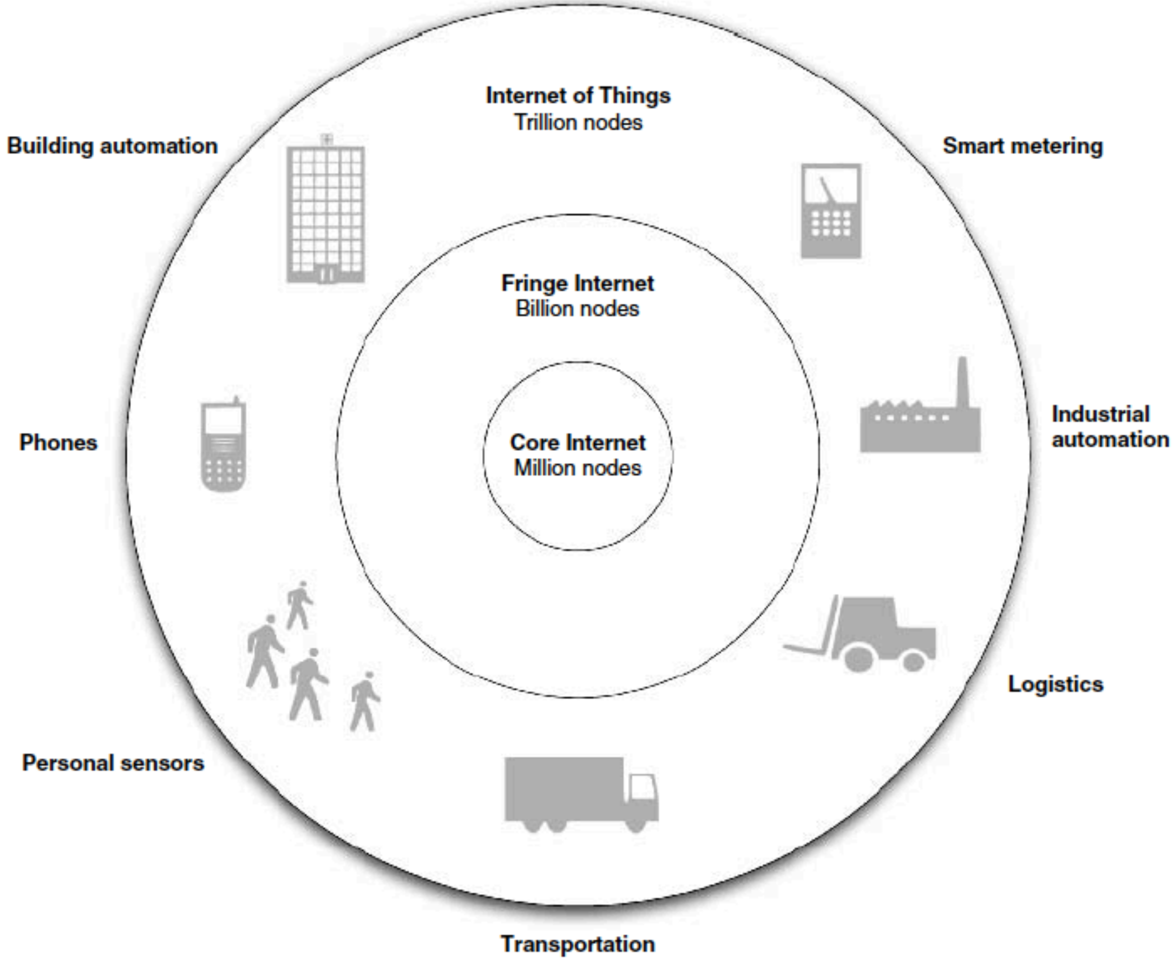
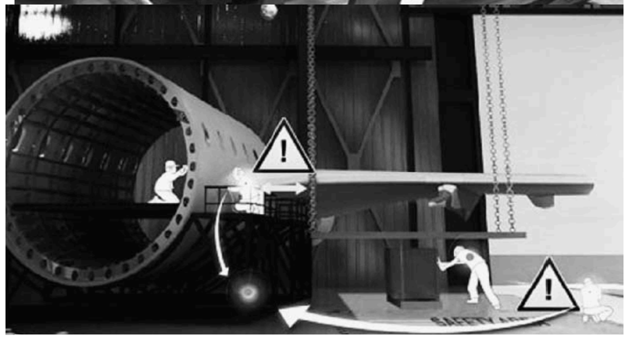
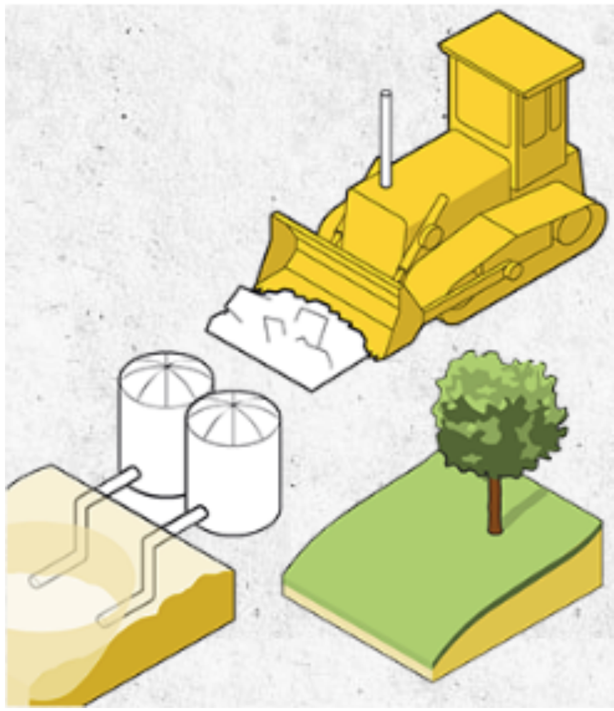
IoT Applications







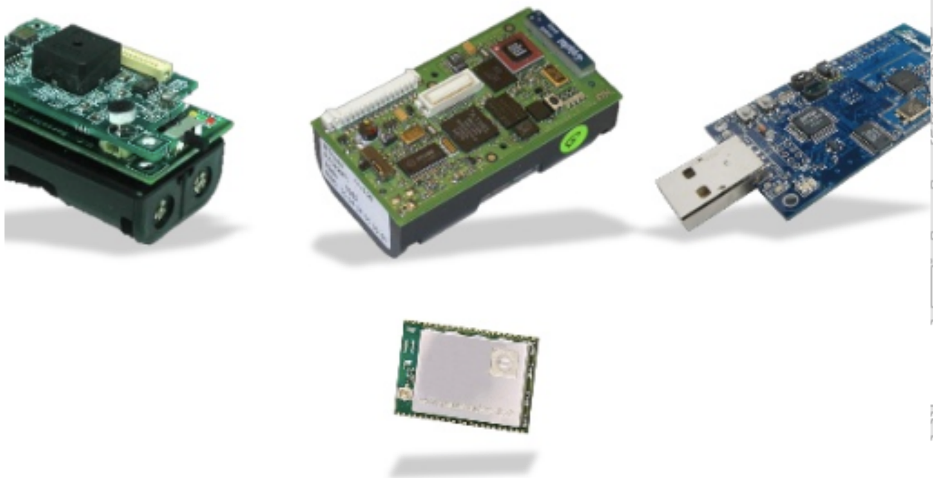
IoT Standardization

- ✓ IEEE 802.15.4, first low-power radio standard (2003)
- ✓ ZigBee alliance: proprietary solutions for ad hoc control network (recently opened up to some ideas of 6loWPAN)
- ✓ IPSO (IP Smart Objects alliance) founded in 2008 to promote use of IP protocols by smart objects and promote IoT
- ✓ IETF 6loWPAN: enable effective use of IPv6 on low power low rate simple embedded devices (2005)← initiated by the initiative also of a group of european industry and research organization, some preliminary contributions in the EC SENSEI project
- ✓ IETF Routing over low power and Lossy Networks (ROLL), 2008
- ✓ ISA 100 industrial automation standard (2008)

From Internet to IoT

- ✓ Success of Internet → over one billion user;
- ✓ Open standards, evolution with technology needs.

Differences between the two worlds: Resources, Reliability, Bandwidth, Scale

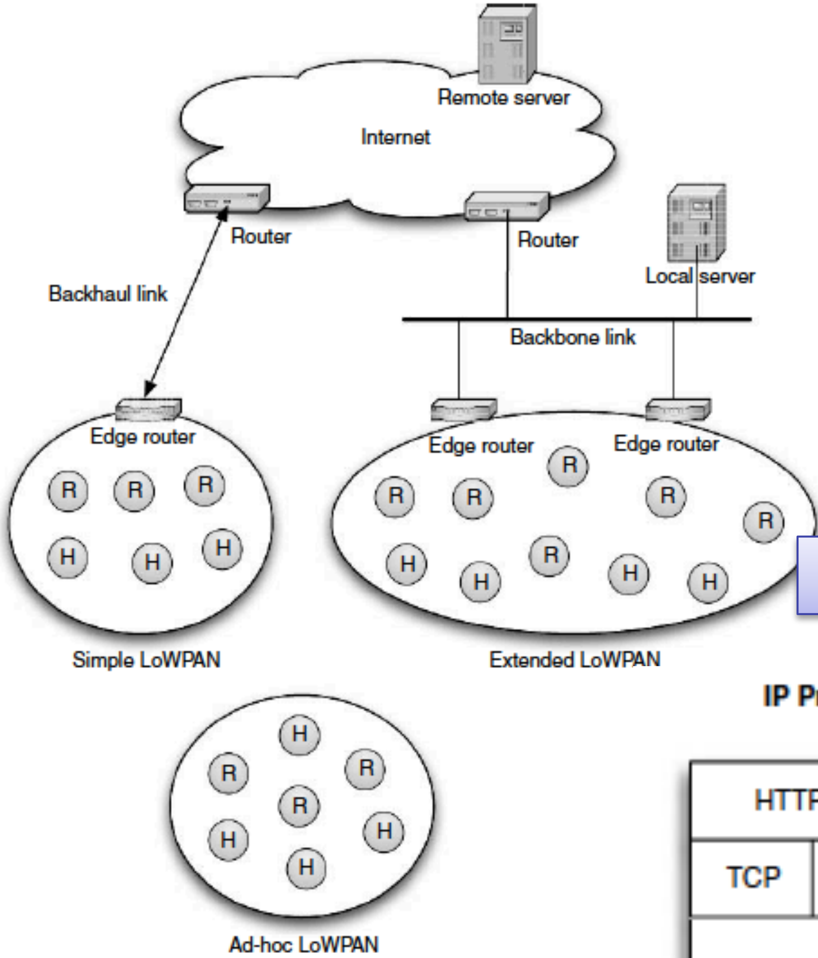


- ✓ Smart objects connected to the Internet
- ✓ 50 billion devices expected to be connected by 2020

6LoWPAN

LOW POWER WIRELESS AREA NETWORKS (LOWPAN)

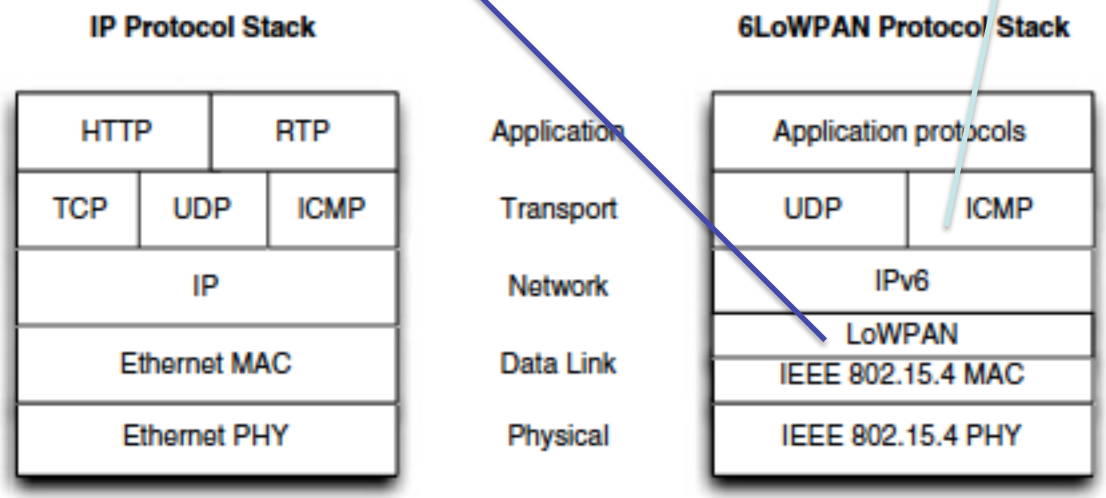
- ✓ STUB IPV6 NETWORK
- ✓ NODES SHARE IPV6 PREFIX
- ✓ CONNECTED THROUGH THE INTERNET VIA A ROUTER OR OPERATING IN AD HOC MODE



Adaptation layer

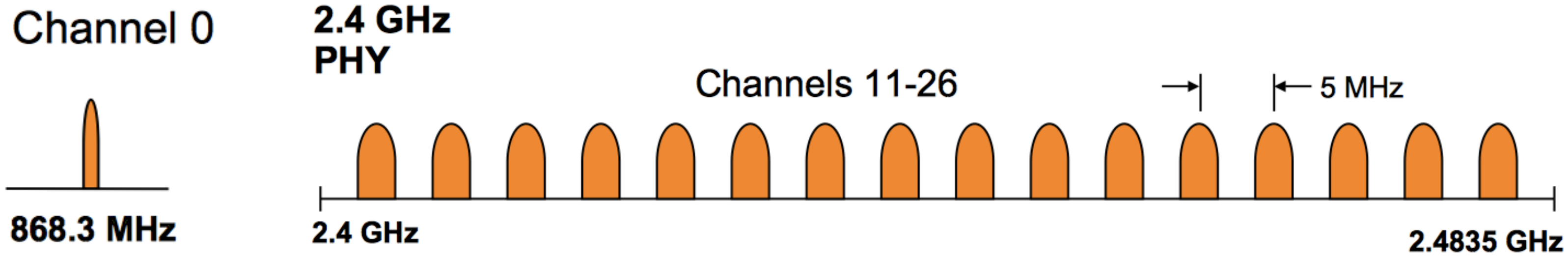
Control messages

Neighbor discovery



IEEE 802.15.4

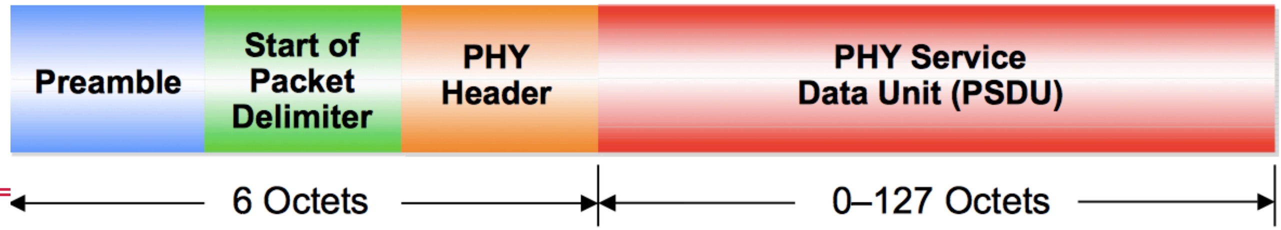
- ISM 2.4Ghz (16 channels), 868MHz (1 channel)



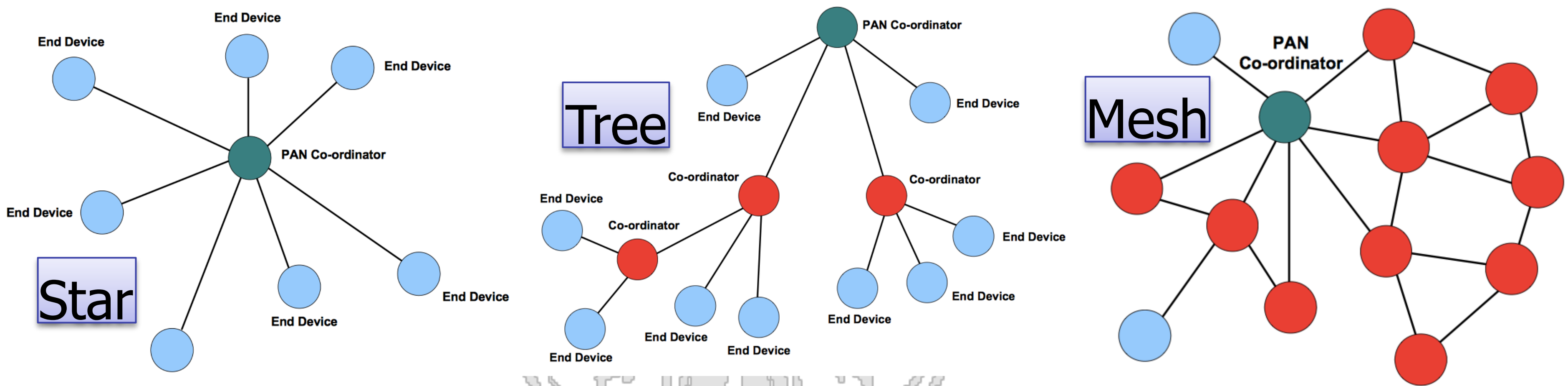
- 20Kbps (868Mhz)-250Kbps (2.4Ghz)
- Packet structure:

PHY Packet Fields

- Preamble (32 bits) – synchronization
- Start of Packet Delimiter (8 bits)
- PHY Header (8 bits) – PSDU length
- PSDU (0 to 1016 bits) – Data field



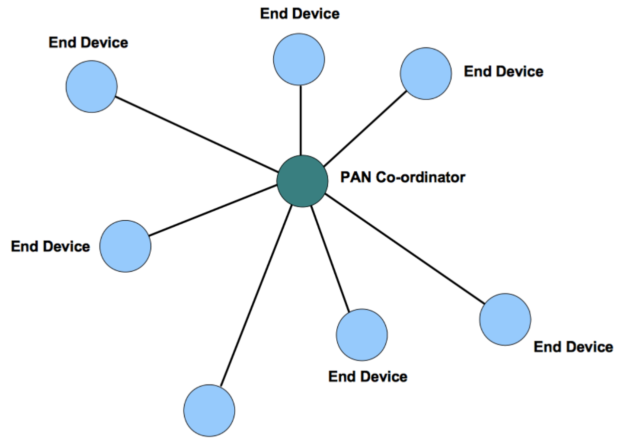
- Very low power operation
  - low power transmitter/receiver
  - nodes can duty cycle
- Topologies:



  - PAN coordinator: Net ID assignment; Frequency selection; handling request to join; packet relaying
  - Co-ordinator: handling request to join; packet relaying

IEEE 802.15.4
How a network is started

- PAN coordinator election
- PAN coordinator assigns itself a short 16 bit address (not IEEE 64 bit addresses)
- Selects the frequency
- Nodes entering the network perform active scan; discover coordinator
- Send an association request, which is ACK-ed
- PAN coordinator may assign a 16bit address to the joining node



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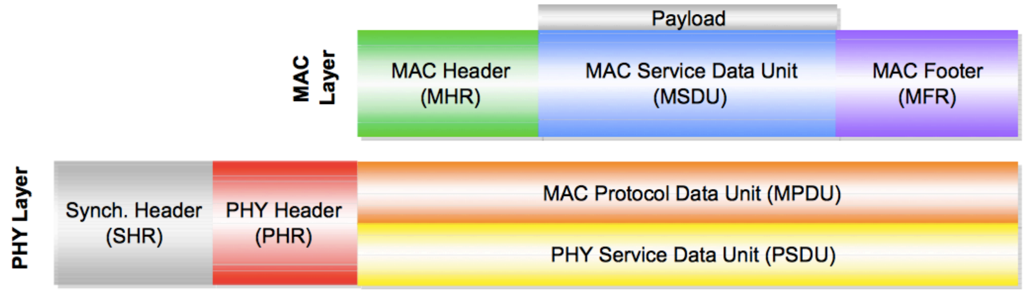
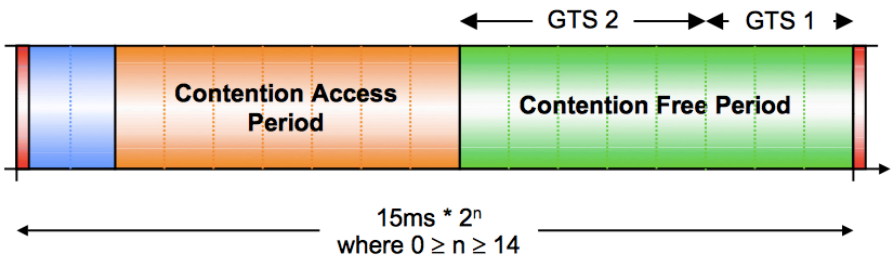
IEEE 802.15.4 MAC



✓ CSMA/CA Based in Beaconless Mode

✓ In Beacon Mode:



Network Beacon—Transmitted by network coordinator. Contains netw
information, frame structure and notification of pending node message

Beacon Extension Period—Space reserved for beacon growth due tc
pending node messages

Contention Period—Access by any node using CSMA-CA

Guaranteed Time Slot—Reserved for nodes requiring guaranteed
bandwidth [n = 0]

IEEE 802.15.4 MAC

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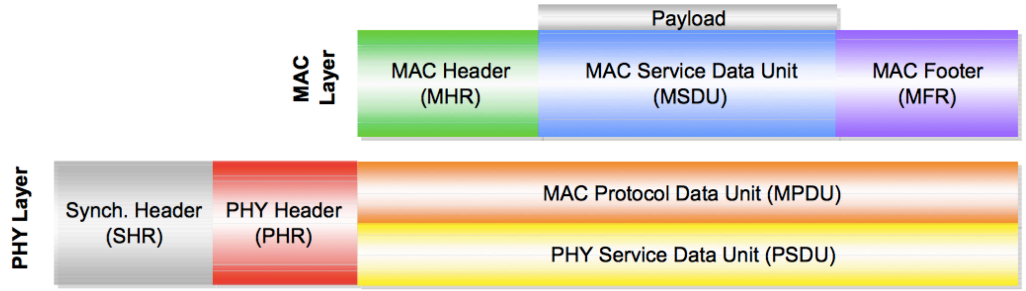

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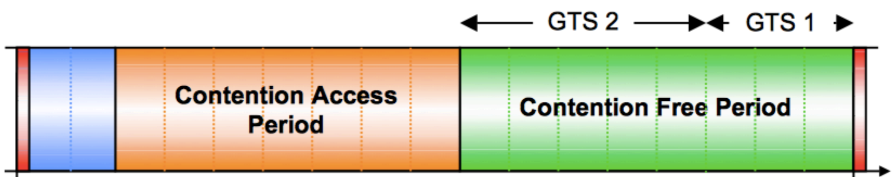

IEEE 802.15.4e envisions

Other types of MAC

Data frames for the transport of actual data, such as IPv6 frames packaged 6LoWPAN format specification;

Acknowledgment frames that are meant to be sent back by a receiver immediately after successful reception of a data frame, if requested by the acknowledgment request bit in the data frame MAC header;

MAC layer command frames, used to enable various MAC layer services such as association to and disassociation from a coordinator, and management of synchronized transmission; and

Beacon frames, used by a coordinator to structure the communication with its associated nodes.

- Addressing: not routable local addresses. Smart objects are permanently identified by EUI-64 identifiers (8 bytes)
  - short 16 bit local address is assigned during network bootstrapping to reduce overhead

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     OUI      |L|M|           OUI (cont.)          |              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+                +
|                      extension identifier                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

- OUI= Organizationally Unique Identifier
- IPv6 address can be (and must be in 6LoWPAN) obtained by concatenating a 64bit network address with the EUI-64

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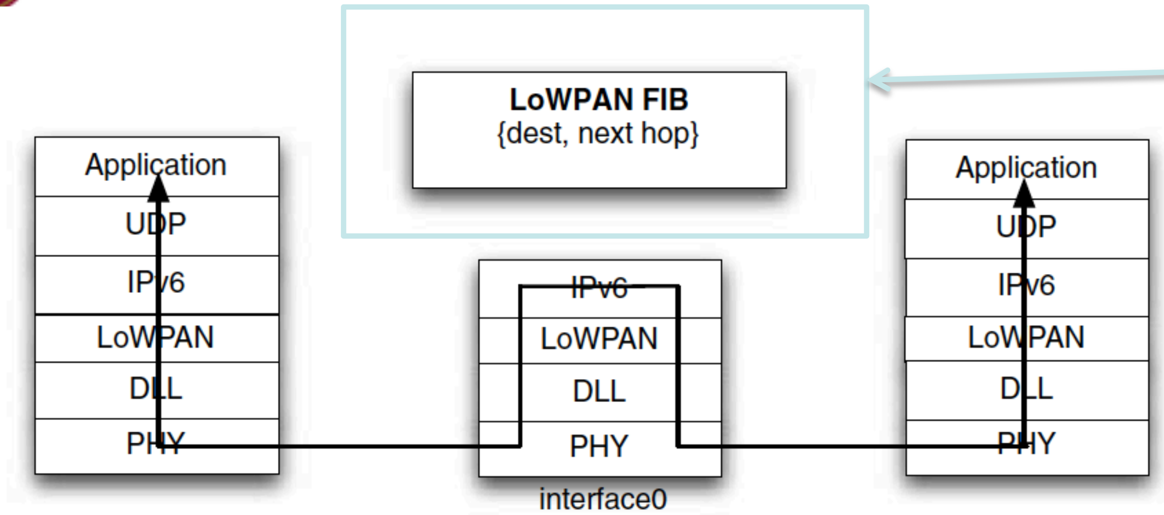
6LoWPAN Routing



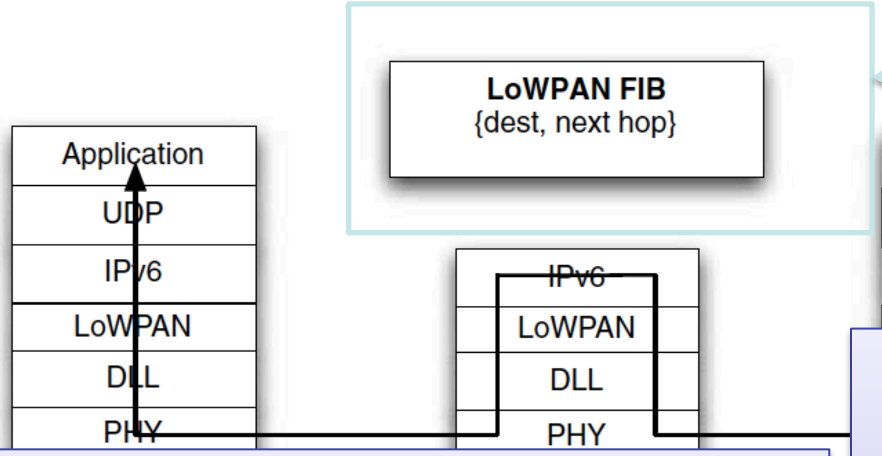
Updated by the selected routing protocol

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 0|V|F|HopsLft| originator address, final address ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 0|V|F|1 1 1 1|   Hops Left   | originator address, final address...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch   /
```

Specifies type and subtype of the header (i.e., which is the meaning of the following information, how many bits are allocated to each field)

6LoWPAN Routing



Updated by the selected routing protocol

V and F bits say whether a 64 or 16 bit Address will follow

We need info on very first node (V—source node), e.g., for reassembly, and on final destination (F) for routing. Such information are always provided In the mesh header (which is the first Header in multi-hop nertworks)

```
 0
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
|1 0|V|F|HopsLft| originator address, fi
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-

+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 0|V|F|1 1 1 1|   Hops Left   | originator address, final address...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch   /
```

Specifies type and subtype of the header (i.e., which is the meaning of the following information, how many bits are allocated to each field)

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Header Compression

- Limited Packet size
- Transmitting 128bits addresses + information needed for security purposes can lead to very high overhead
- Solution: header compression
  - Stateless header compression
    - ✓ HC1: compresses IPv6 headers
    - ✓ HC2 compresses UDP headers

HC1 compression

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |0|       Non-Compressed fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch   _/ \_ HC1 header_/
```

Identifies that an HC2 header follows

```
 0                   1                   2
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |1|S|D|L|_________| N.-C. fie
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
 \_ dispatch   _/ \_ HC1 header_/ \_ HC2 header_/
```

Header Compression

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- Solution: header compression
  - Stateless header compression

Used to avoid transmitting First 64 bits of the address

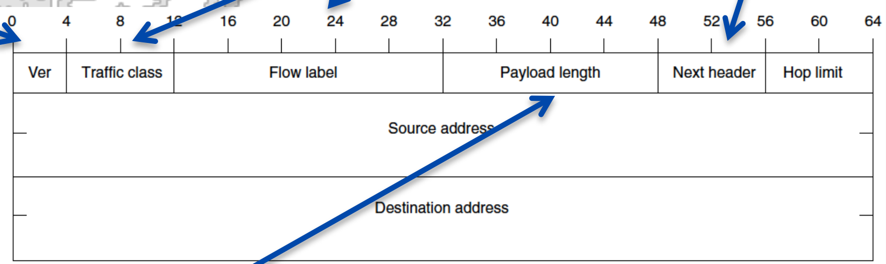
Always 6 not transmitted in HC1

Often 0. C=1 means their values are zero

Some likely values (UDP,TCP,ICMP) expressed by The two bit NH. If NH !=0 can be skipped

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |0|      Non-Compressed fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/ \_ HC1 header_/

 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |1|S|D|L|_________| N.-C. fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/ \_ HC1 header_/ \_ HC2 header_/
```



IPv6 packet header

Can be inferred by other Headers--Not transmitted

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+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |0|      Non-Compressed fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/ \_ HC1 header_/

 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |1|S|D|L|_________| N.-C. fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/ \_ HC1 header_/ \_ HC2 header_/
```

Source/destination port field compression
How? favoring port selection among a subset of possible ports

Indicates length size can be inferred and is thus not included

Fragmentation

- Used when transmitting L2-L3 PDU larger than 128 bytes
- Fragmentation/reassembly performed at the link level.

Fragmentation header:

Together with source/destination used to identify the original packet

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 1 1 0 0|    datagram_size     |         datagram_tag          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|datagram_offset|
+-+-+-+-+-+-+-+-+
 \_ dispatch  _/
```

Identifies order of fragment within the sequence of fragments of the same packet

- Compression again as key apect for header design.

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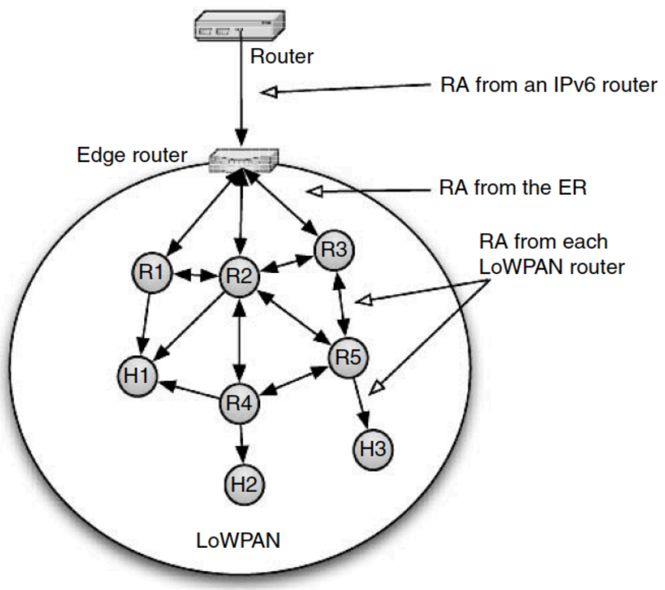
Bootstrapping an IoT network

- Edge Router broadcasts general information
- Association procedure for new nodes (they select the router to affiliate to based on ER metric; Node registration/ confirmation)
- Procedure to assign local addresses, identify and solve duplicate addresses.




```
 0                   1
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0|1|LOWPAN_BC0 |Sequence Number|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/
```

Broadcast packet

Bootstrapping an IoT network

- Edge Router broadcasts general information
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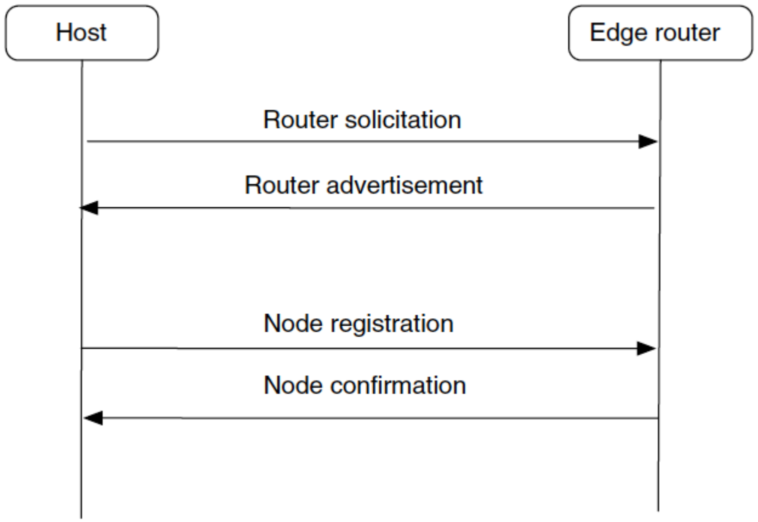
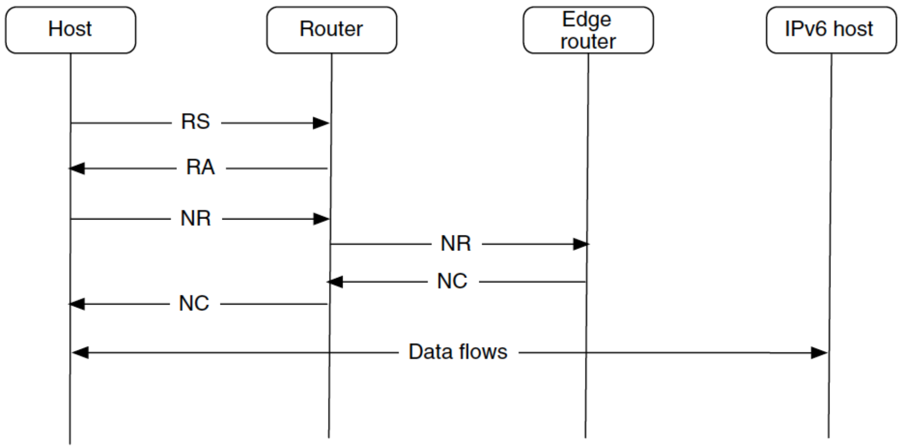



```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Type (NR)/(NC)|     Code      |           Checksum            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      TID      |    Status     |P|_____________________________|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|       Binding Lifetime        |     Advertising Interval      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Owner Nonce                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                   Owner Interface Identifier                  +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|   Registration option(s)...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |    Length     |    Status     |   S   |   P   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|D|A|R|_________________________|         IPv6 Address        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Bootstrapping an IoT network

- Edge Router broadcasts general information
- Association procedure for new nodes
- Procedure to assign local addresses, identify and solve duplicate addresses.

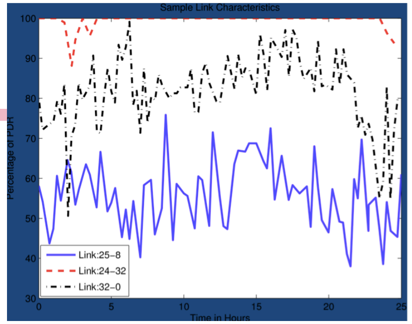



```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Type (NR)/(NC)|     Code      |           Checksum            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      TID      |    Status     |P|_____________________________|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|       Binding Lifetime        |     Advertising Interval      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                          Owner Nonce                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                   Owner Interface Identifier                  +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Registration option(s)...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

```
 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |    Length     |    Status     |   S   |   P   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|D|A|R|_________________________|         IPv6 Address       ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

- Desirable features
  - Energy aware, small factor, lightweight solutions, low overhead
  - Should scale to thousands of smart objects
  - Long lasting systems (years or decades)
  - Auto-configuration, self-managing
  - Robust even in presence of varying link quality and unreliable links

ROLL--Routing Over Low power and Lossy



- “Ripple” routing protocol RPL-- Proactive distance vector routing;
  - specifies how to build a destination oriented acyclic graph (DODAG)
- Multi-hop support
- Flexible metric
  - <Find paths with the best ETX and avoid non encrypted links> or <Find the best path in terms of latency while avoiding battery operated nodes>.
  - Administrator may decide to have multiple routing topologies active at the same time to carry traffic with different requirements
  - dynamic metrics (link quality, CPU overload, battery levels, all fast changing over time…)
- Focus on energy constrained, secure solutions
- Routing supported across multiple types of link layers

RPL– DODAG formation

- RPL specifies how to build a destination oriented acyclic graph (DODAG)
- Root (ER) sends a DIO (DODAG Information Object) message
- Neighbors of the root will listen to the DIO and decide whether to join DODAG. They can decide to become a router and re-forward the DIO.
  - Each of their neighbors, upon receiving the DIO, selects its parent (according to a suitable metric) and –if it decides to become a router- reforwards the DIO.

This rippling effect builds the graph edges out from the root to the leaf nodes where the process terminates.

RPL – How to multicast messages

- Destination Advertisement Object (DAO) advertises prefix reachability towards the leaf nodes [prefix information/lifetime/distance from the prefix]
- As a node joins the graph it sends a DAO to its parent (can also be solicited)
- DAO messages are forwarded till the root
- Prefix reachability info exchange also enables peer to peer communication
  - up along the tree till the common ancestor, then down till the intended destination

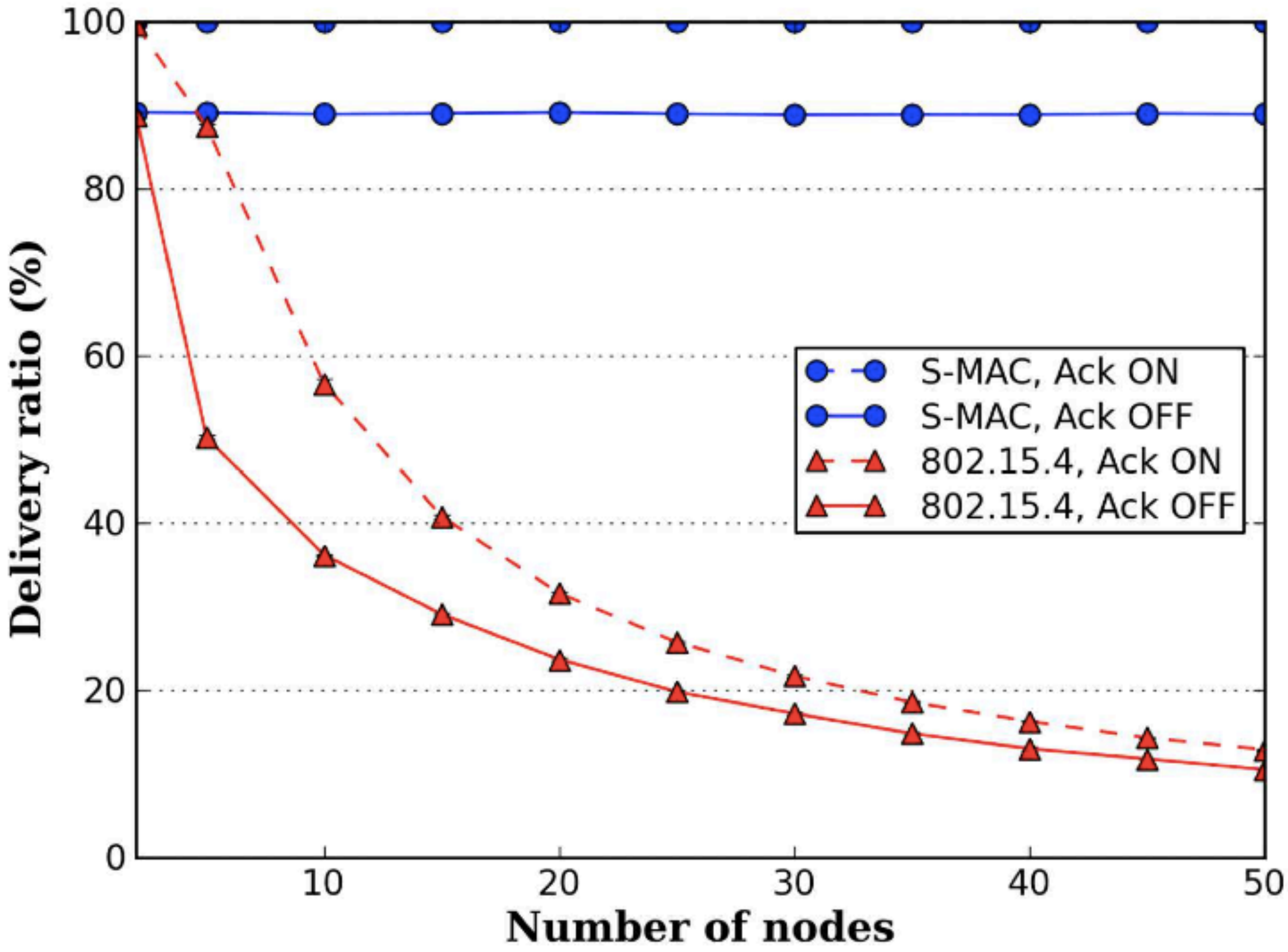
RPL –trickle timers

- How often are DIO messages sent?
  - Dynamically selected (trickle timer) based on how stable the system is
  - If the system stabilizes it is seldom sent
  - Whenever an inconsistency is detected (such as loop or changes in the DODAG) then the timer is reset to small values

Limits of standard approaches

- Still unstable
  - Despite there has been significant improvements in the direction of well conceived standards in the last few years, the field is still experiencing significant evolution in standards and it is not clear which standard will succeed;
- Standards fail to capture emerging paradigms
  - ✓ Zero power sensing systems (energy harvesting enabled, wake up radio enabled)
  - ✓ Cutting edge protocols and security solutions
  - ✓ Standards do not lead to the best performance
- Available open implementations have several bugs
  - Significant work required to develop effective robust solutions

An example of performance loss



In Summary

- Standardization is important
  - Key for interoperability
  - Key for IoT success
  - Seamless integration to Internet favors application and service development
- Will come…
  - Trend towards open standards will likely allow to fast incorporate results of research and novel trends
- Transient scenario:
  - Companies proposing fully standard compliant solutions coexist with companies using legacy protocols/solutions tillgateway which is then interconnected to Internet via standard protocols.

IoT integration with mobile systems

- Air interface for M2M
  - data rate vs. energy consumption
  - heterogeneous QoS requirements
- Energy consumption
  - decrease in energy consumption through use of harvesting, wake up radio technologies and passve backscattering
- Synchronized bursty IoT transmission could severely degrade 5G cellular systems
  - → Coordinated access
  - → Minimization of the amount of transmitted traffic (es. anycasting)