IoT Standardization

Internet of Things a.a. 2019/2020

Un. of Rome “La Sapienza”

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Phy, MAC and network protocols

- ✓ IEEE 802.15.4, first low-power radio standard (2003)
- ✓ ZigBee alliance: proprietary solutions for ad hoc control network (first solutions since 2006 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)

Phy, MAC and network protocols

Low Power WAN

- ✓ LoRa
- ✓ SigFox

Cellular Networked Based

- ✓ NB-IoT

IoT variants of traditional WLAN wireless comm

- ✓ Bluetooth Low Energy
- ✓ low power WiFi

IoT Standardization

Upper layer protocols and integration with remote Control platforms

- ✓ COAP (Constrained Application Protocol)
- ✓ MQTT (Message Queueing Telemetry Transport)
- ✓ AMQP (Advanced Message Queuing Protocol)

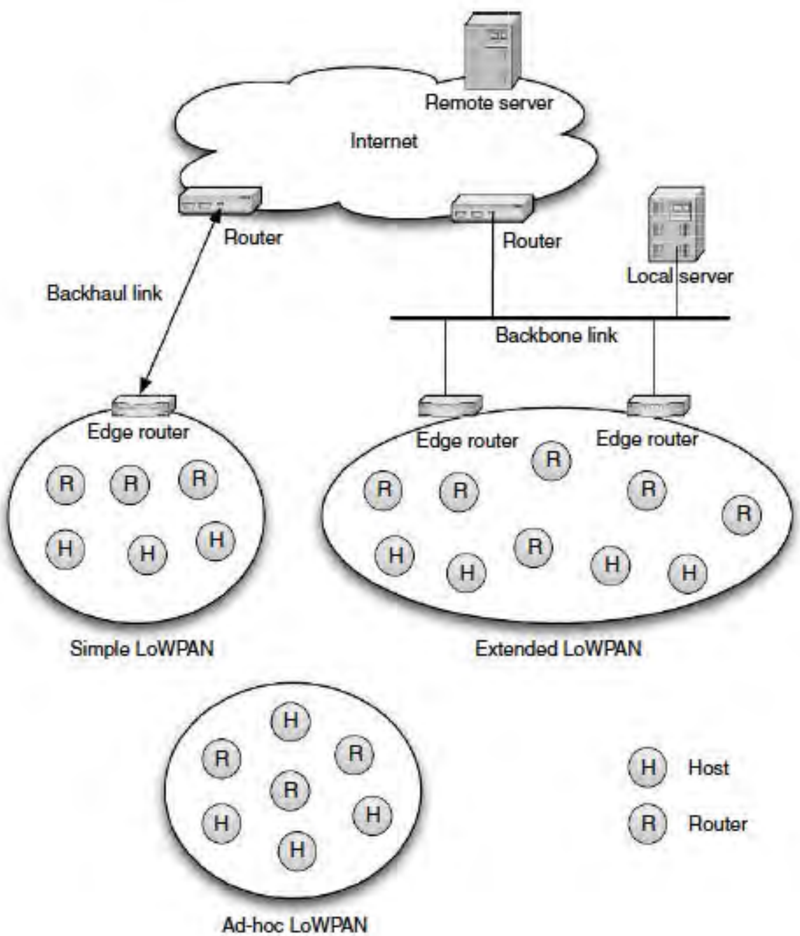
Platforms for IoT

- ✓ AWS IoT (Cloud)
- ✓ Azure (Cloud)

…

- ✓ Proprietary SW platforms (typically based on microservice paradigm)

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

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6LoWPAN

All the solutions we have described are able to operate in IEEE 802.15.4 compliant networks

LOW POWER WIRELESS AREA NETWORKS (LOWPAN)

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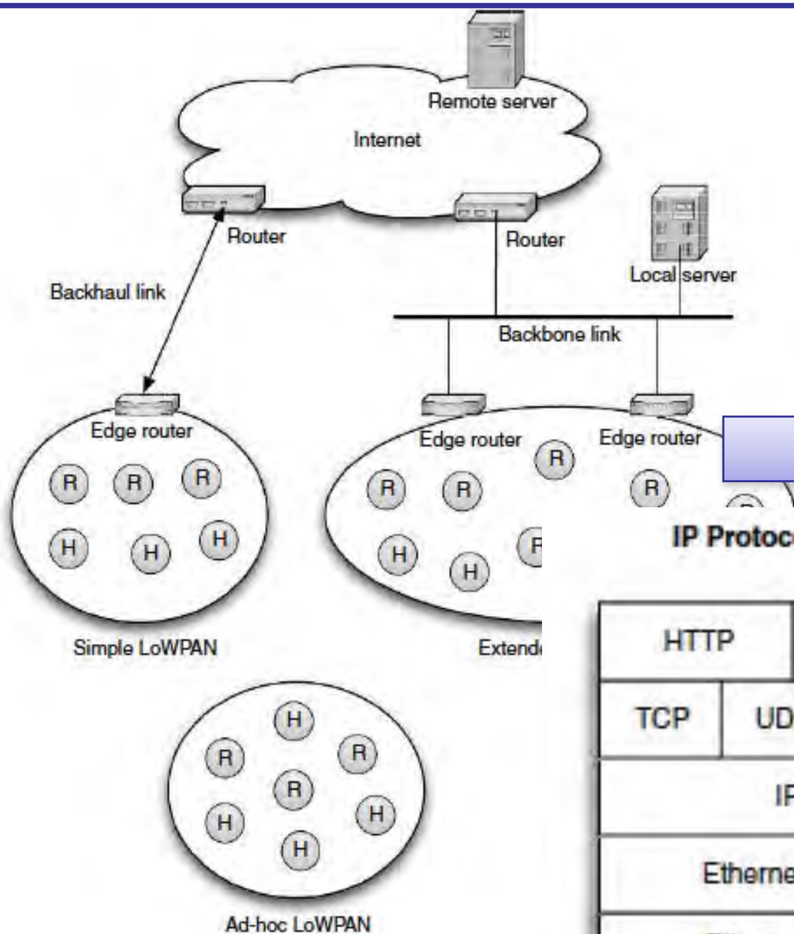
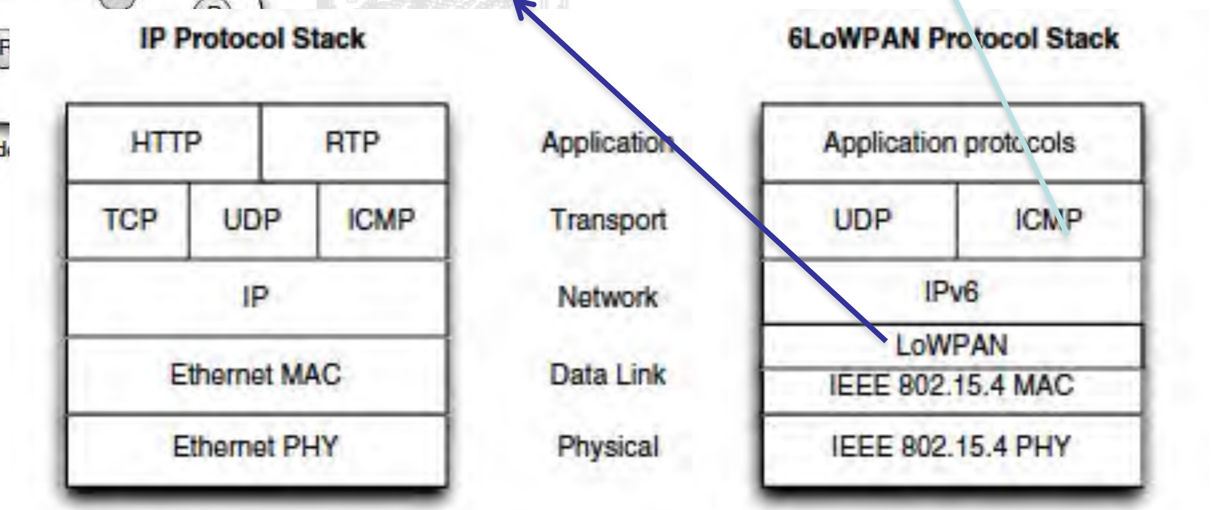


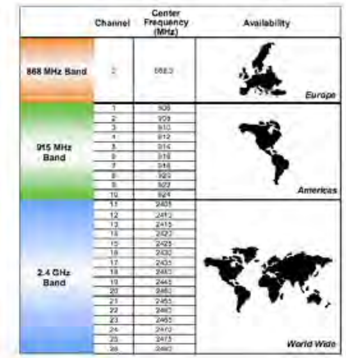
Control messages

Neighbor discovery

Adaptation layer



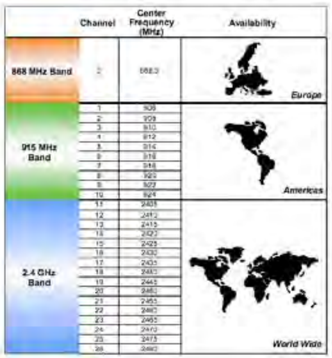
IEEE 802.15.4



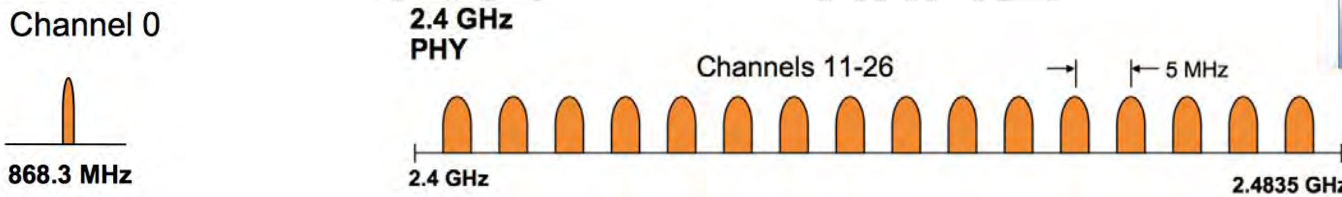
- Material to read: http://users.eecs.northwestern.edu/~peters/references/ZigtbeeIEEE802.pdf

Chapter 2, 3, 4

IEEE 802.15.4

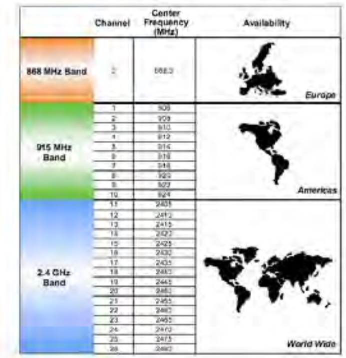


- ISM 2.4Ghz (16 channels), 868MHz (1 channel)



- 20Kbps (868Mhz)-250Kbps (2.4Ghz)
- Phy layer functions:
  energy detection (ED),
  link quality indication (LQI),
  channel selection,
  clear channel assessment (CCA

IEEE 802.15.4



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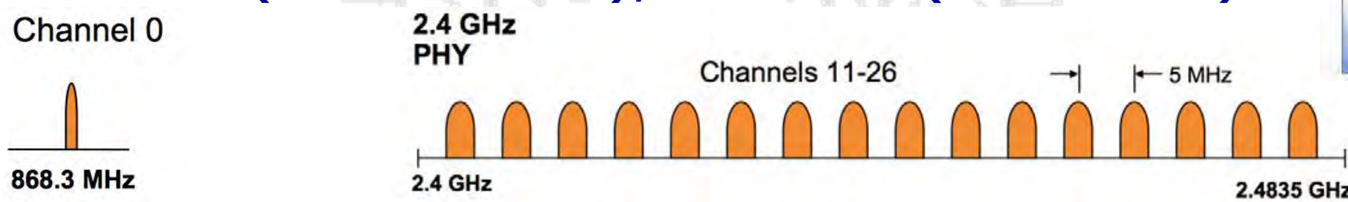
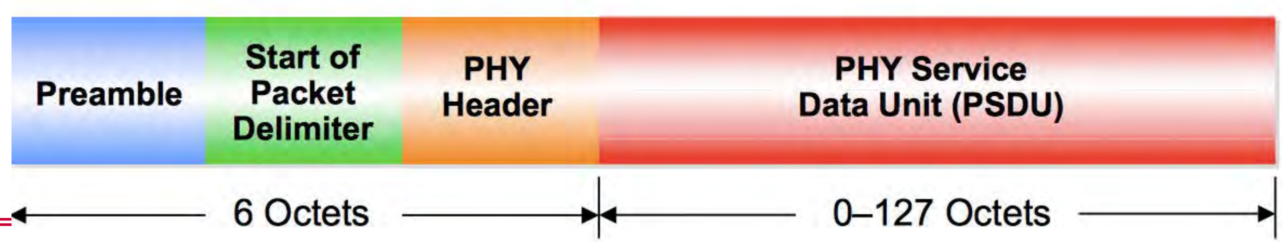


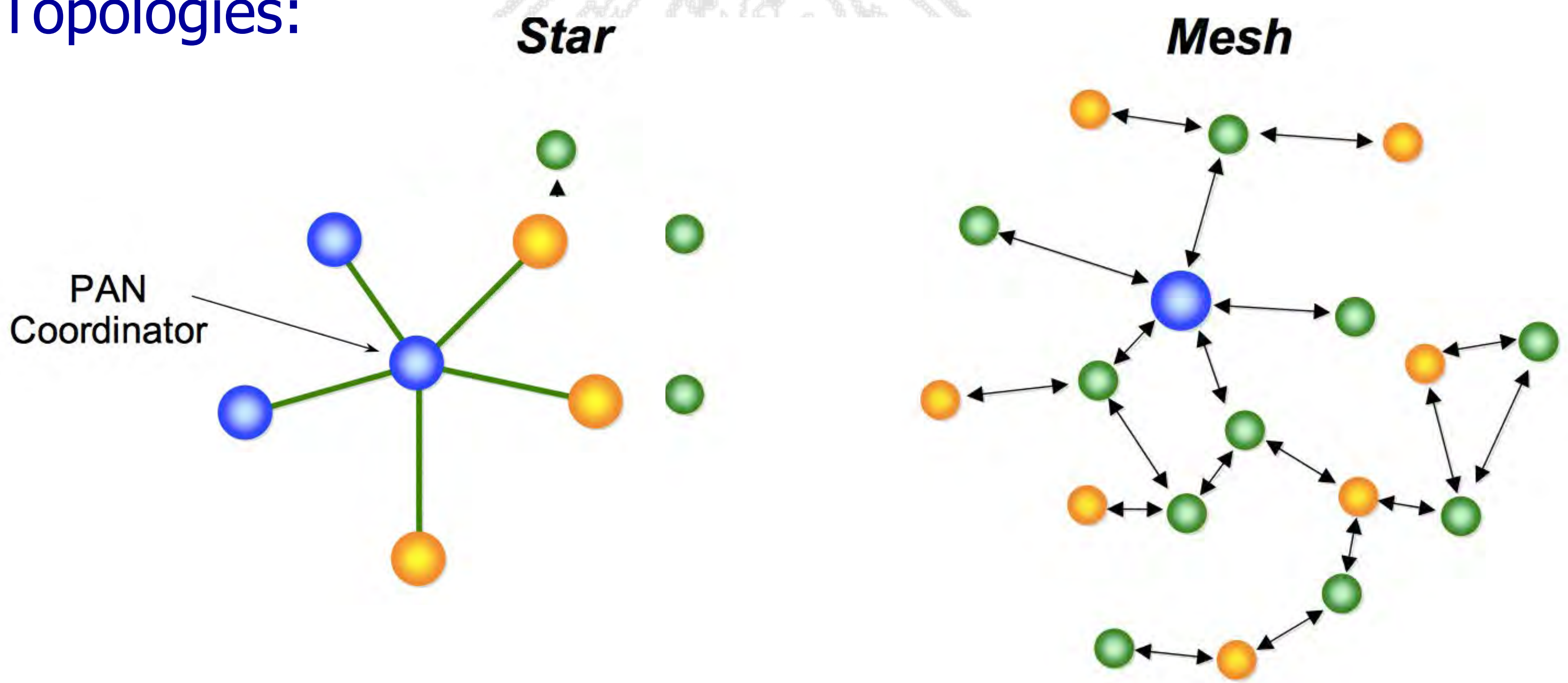
- 20Kbps (868Mhz)-250Kbps (2.4Ghz)
- Phy PDU structure:

PHY Packet Fields

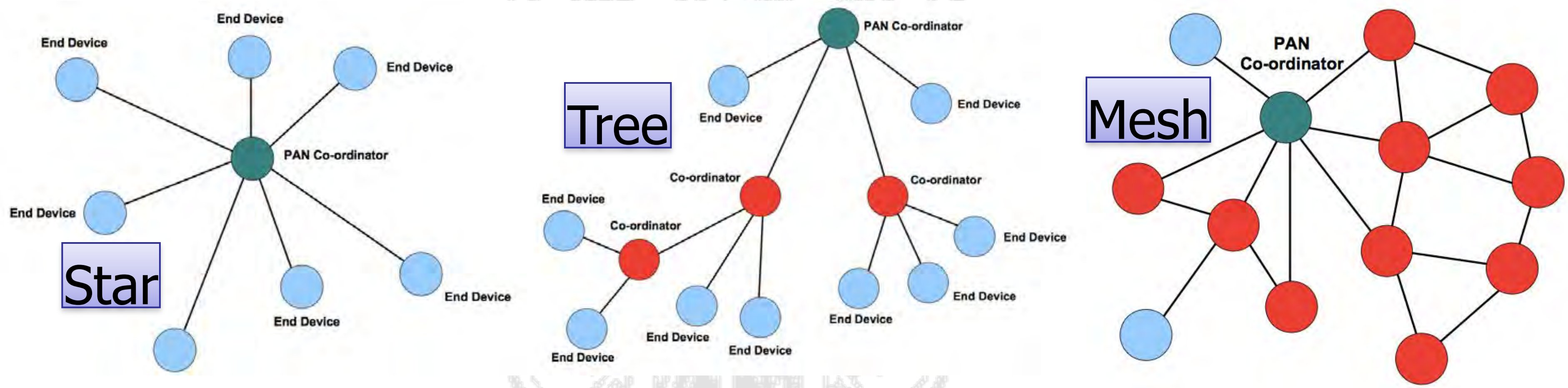
- Preamble (32 bits) – synchronization
- Start of Packet Delimiter (8 bits)
- PHY Header (8 bits) – PSDU length
- PSDU (0 to 1016 bits) – Data field



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



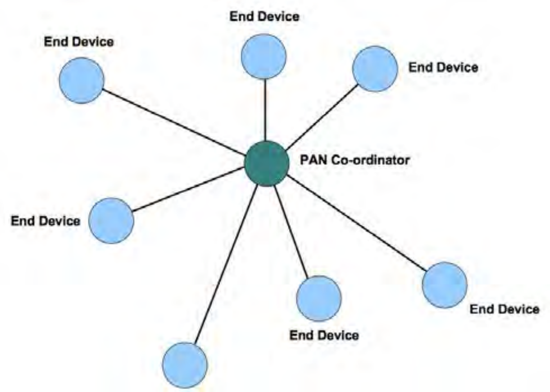
- Very low power operation
  - low power transmitter/receiver
  - nodes can duty cycle
- Topologies:



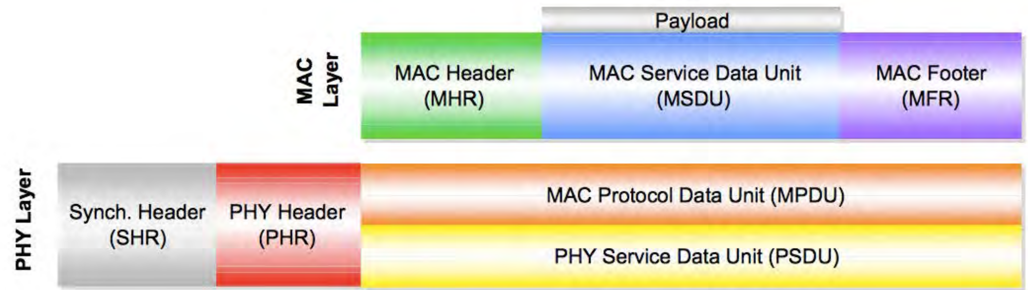
  - PAN coordinator tasks: Net ID assignment; Frequency selection; handling request to join; packet relaying
  - Co-ordinator: handling request to join; packet relaying

IEEE 802.15.4
How a network is started

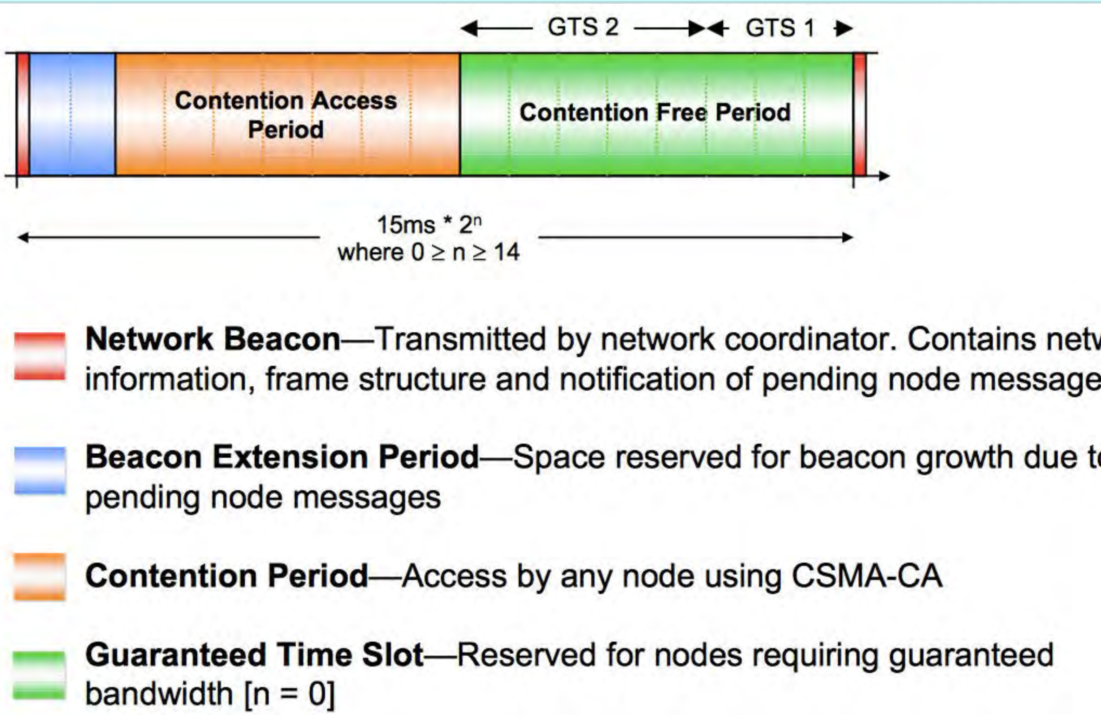
- PAN coordinator election
- PAN coordinator assigns itself a short 16 bit address (not IEEE 64 bit addresses)
- Selects the frequency
- Nodes entering the network perform active scan; discover coordinator
- Send an association request, which is ACK-ed
- PAN coordinator may assign a 16bit address to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



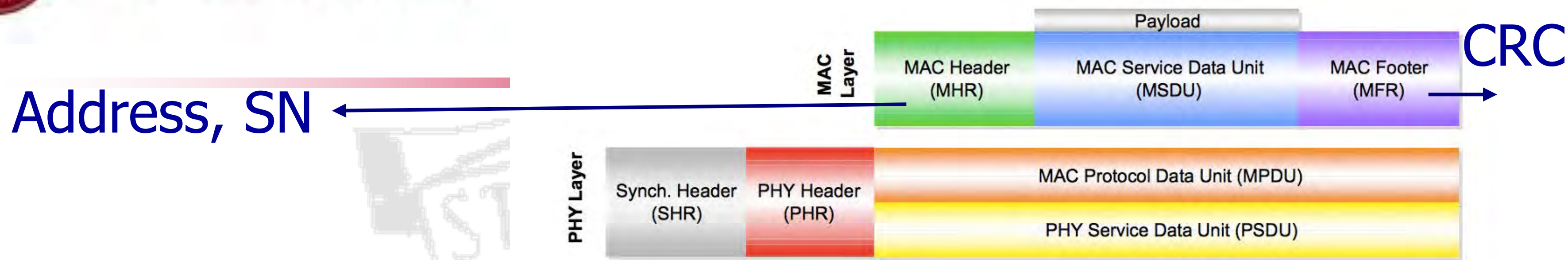
IEEE 802.15.4 MAC



- ✓ CSMA/CA Based in Beaconless Mode
- ✓ In Beacon Mode:

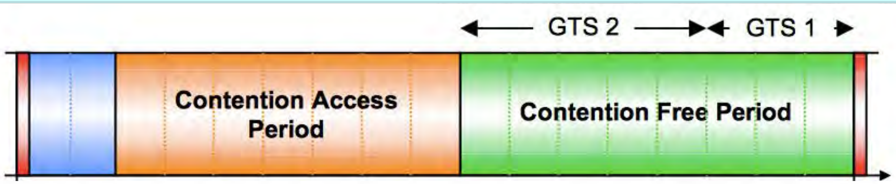


IEEE 802.15.4 MAC



✓ CSMA/CA Based in Beaconless Mode

✓ In Beacon Mode:



IEEE 802.15.4e envisions

Other types of MAC.

Standard extended also to other bandwidth

Data frames for the transport of actual data, such as IPv6 frames packaged according to the 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.

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Beaconless mode

- CSMA/CA
- If a sender has a packet to transmit, it picks a random backoff delay then it listens to the channel (CCA)
- If free then it sends data which is acked
- If busy it retries after waiting for an increased backoff interval

All MAC protocols for sensing systems we have seen assume to operate on an IEEE 802.15.4 compliant networks operating in beaconless mode

Beaconless mode

Beaconless to/from a PAN coordinator

- One element is always on? Node wake up request for possible data stored for them or send data through CSMA/CA

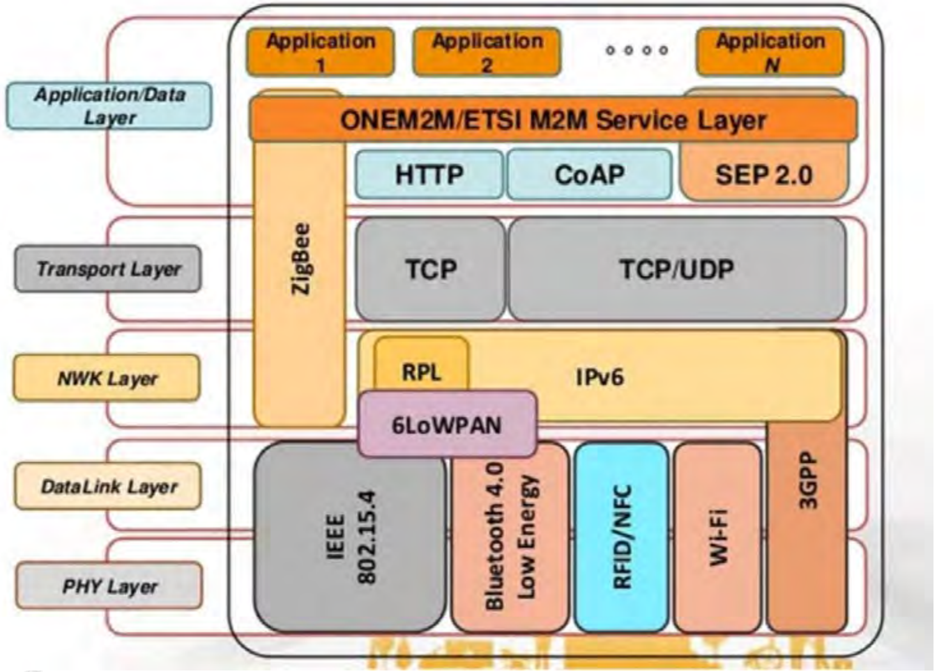
Mesh Network

- Described CSMA/CA protocol
- Nodes duty cycle
- Can be integrated with synchronous/asynchronous MAC protocols we have seen in the last class

IEEE 802.15.4 Applications: ZigBee

First ZigBee protocol stack

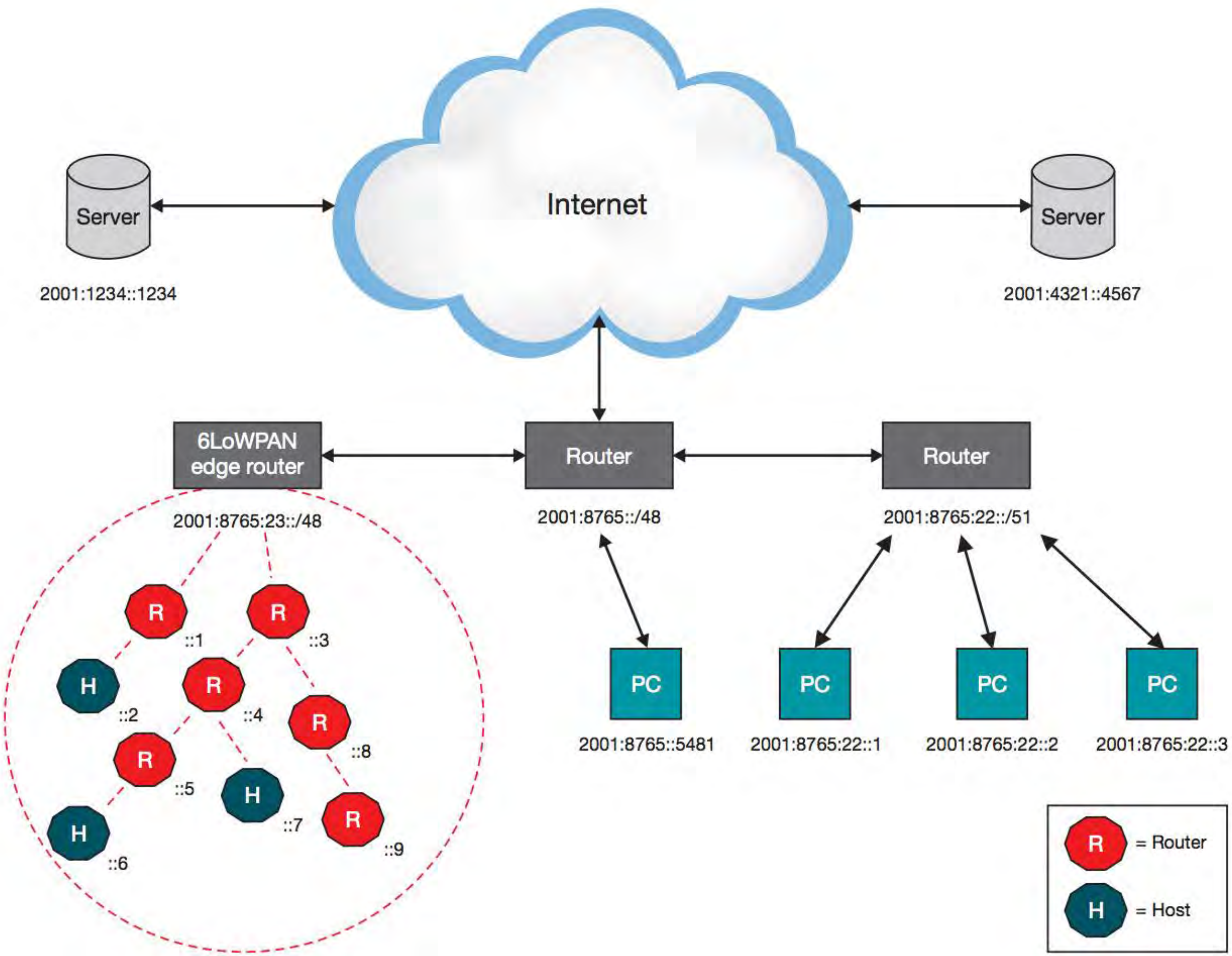
- IEEE 802.15.4
- Lightweigh AODV implementation at the routing layer
- Application layers



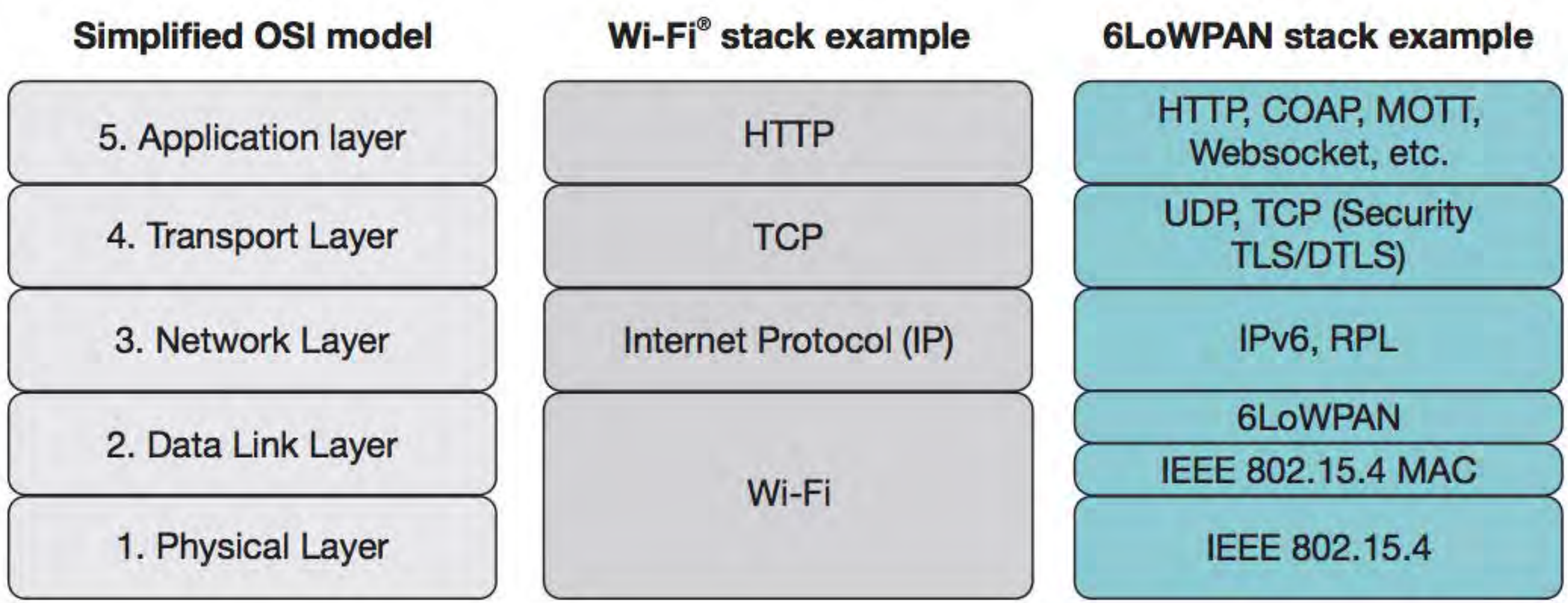
6LowPAN

- See:
- http://www.ti.com/lit/wp/swry013/swry013.pdf
- 6LoWPAN: Incorporating IEEE 802.15.4 into the IP architecture. Internet Protocol for Smart Objects (IPSO) Alliance, White paper # 3. By Jonathan Hui, David Culler, Samita Chakrabarti.

6LowPAN Architecture



IoT com architecture based on 6LowPAN



Adaptation layer: 6LoWPAN

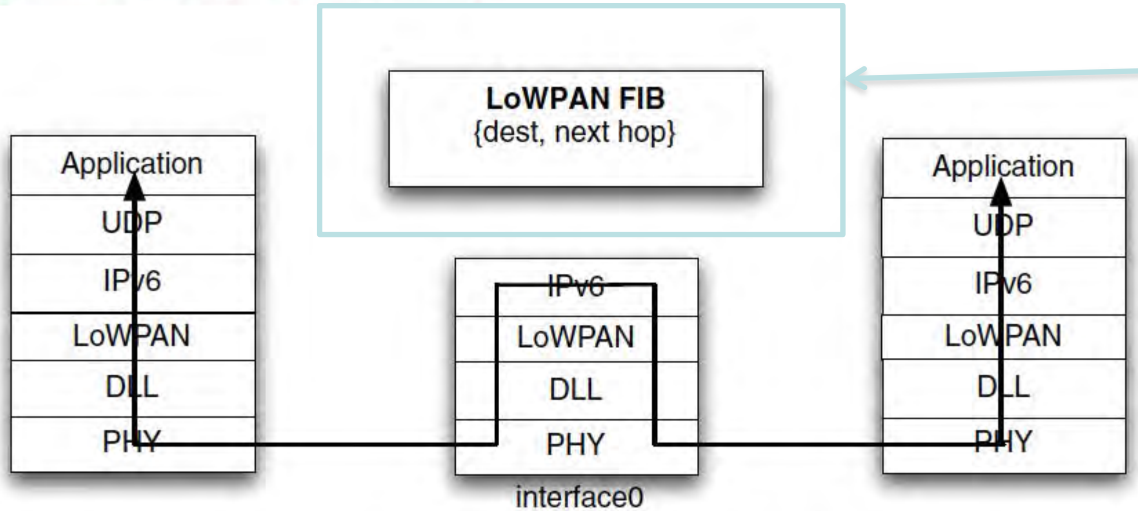
- Addressing: not routable local addresses. Smart objects are permanently identified by EUI-64 identifiers (8 bytes)
  - short 16 bit local address is assigned during network bootstrapping to reduce overhead

```
 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                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

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

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)

The fragmentation header is elided for packets that fit into one single IEEE 802.15.4 frame. The mesh header is not used when sending data over one hop only.

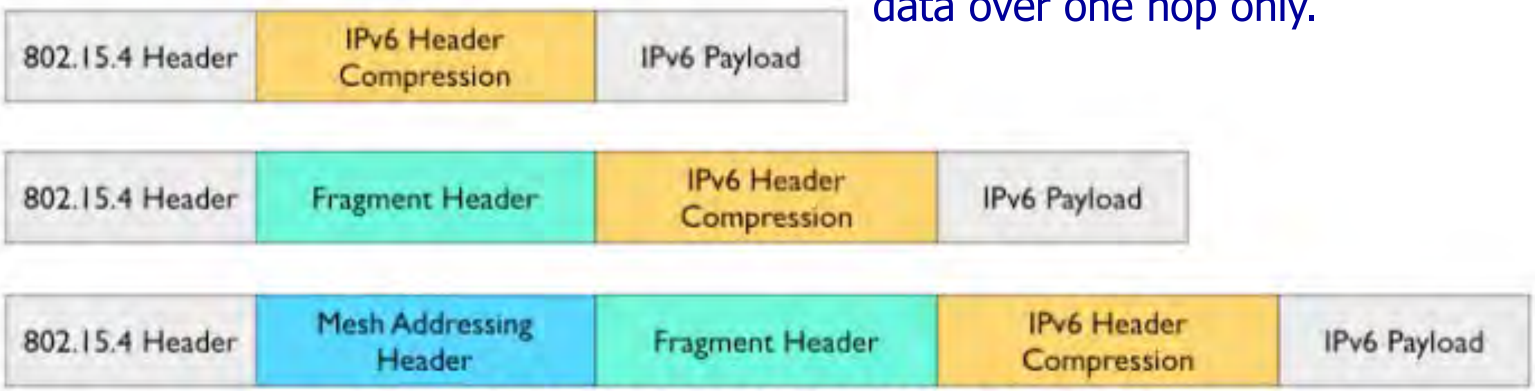


Figure 2. Typical 6LoWPAN Header Stacks.

Figure 3. 6LoWPAN Fragment Header.

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.

Fragmentation

- Used when transmitting L2-L3 PDU larger than 128 bytes
- Fragmentation/reassembly performed at the link level. Fragmentation 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
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|1 1 1 0 0|    datagram_size    |         datagram_tag          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|datagram_offset|
+-+-+-+-+-+-+-+-+
 \_ dispatch  _/
```

Set to zero for the first fragment

- Datagram size describes the total (un-fragmented) payload.
- Datagram tag identifies the set of fragments and is used to match fragments of the same payload.
- Datagram offset identifies the fragment's offset within the un-fragmented payload.
- The fragment header length is 4 bytes for the first header and 5 bytes for all subsequent headers

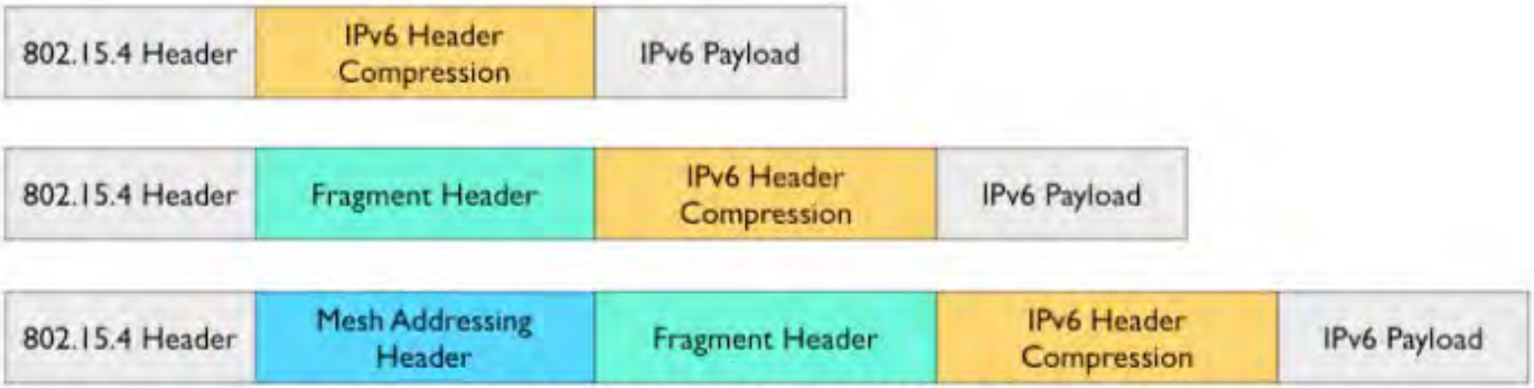
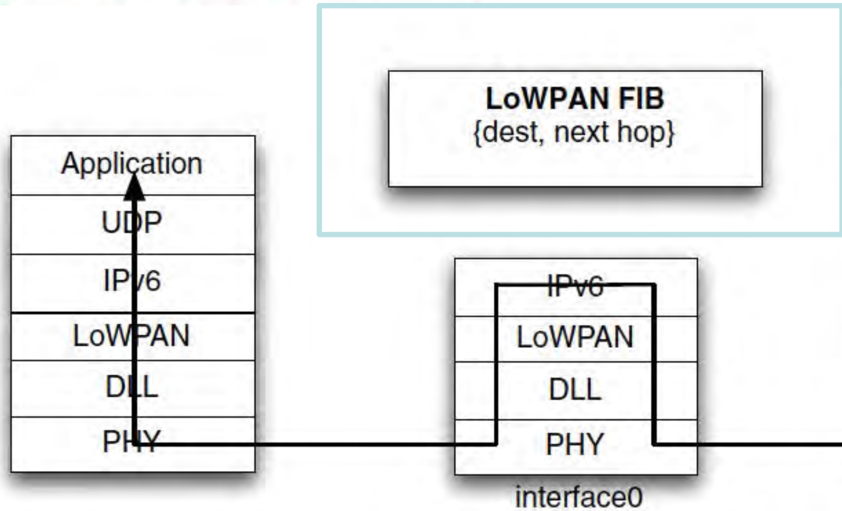


Figure 2. Typical 6LoWPAN Header Stacks.

Figure 4. 6LoWPAN Mesh Addressing Header.

6LoWPAN Routing



Updated by the Selected routing protocol

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

+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
|1 0|V|F|1 1 1 1|    Hops Left    | originator a
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
 \_ dispatch  _/
```

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 networks)

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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6LoWPAN Routing

two categories of routing are defined: mesh-under or route-over. Mesh-under uses the layer-two (link layer) addresses (IEEE 802.15.4 MAC or short address) to forward data packets (the network is seen as a single IP SubNet); while route-over uses layer three (network layer) addresses (IP addresses). In the latter case the routing protocol is RPL.

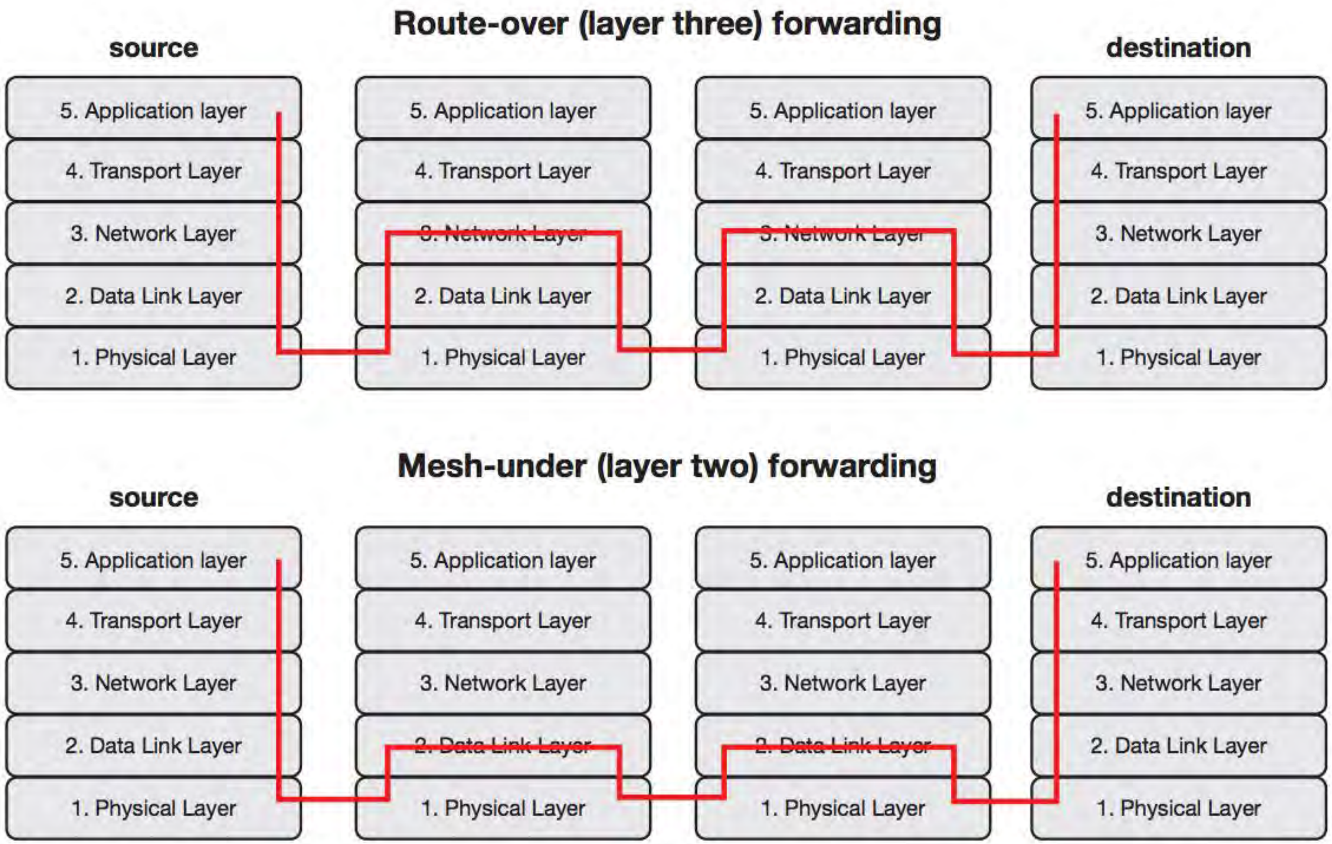
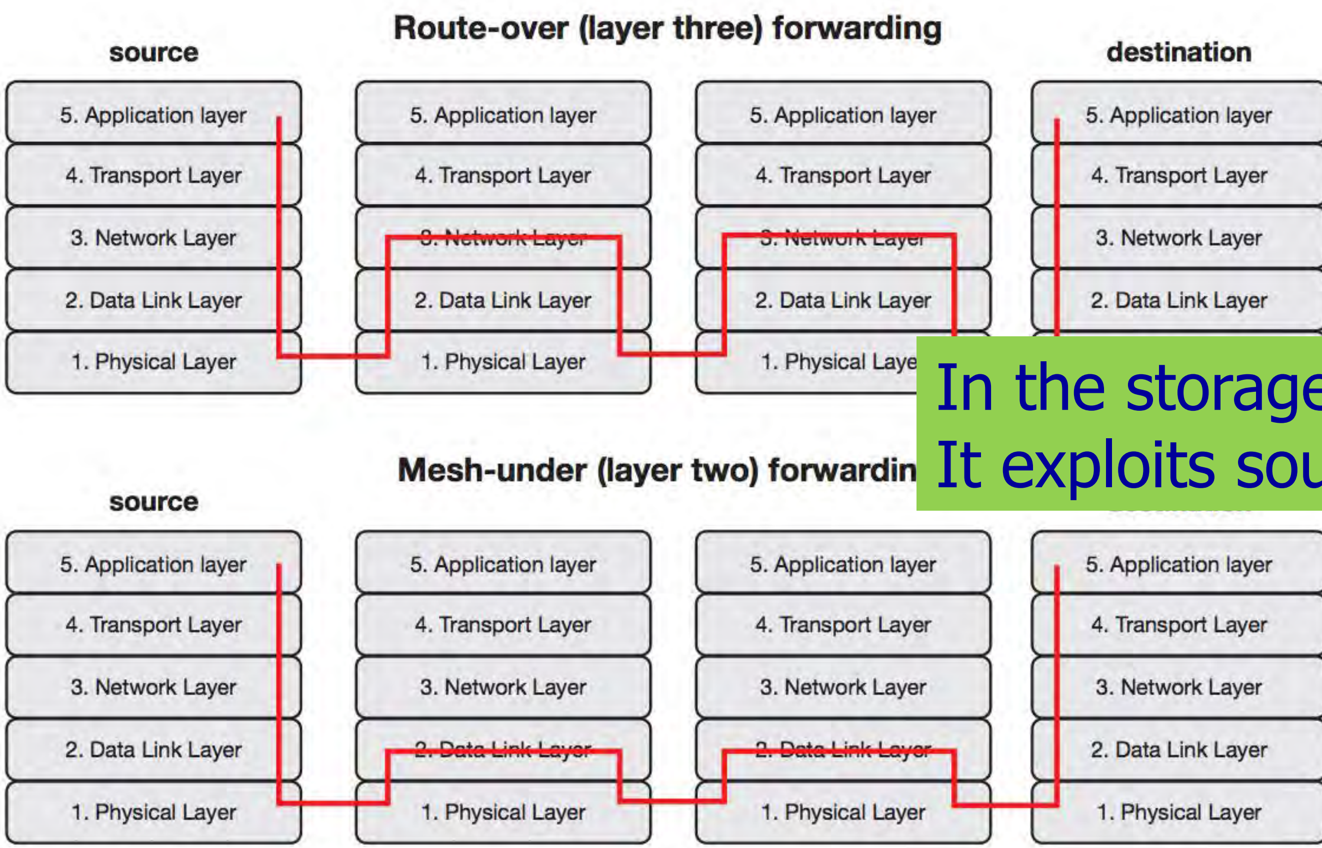


Figure 5. Mesh-under and route-over packet forwarding

6LoWPAN Routing

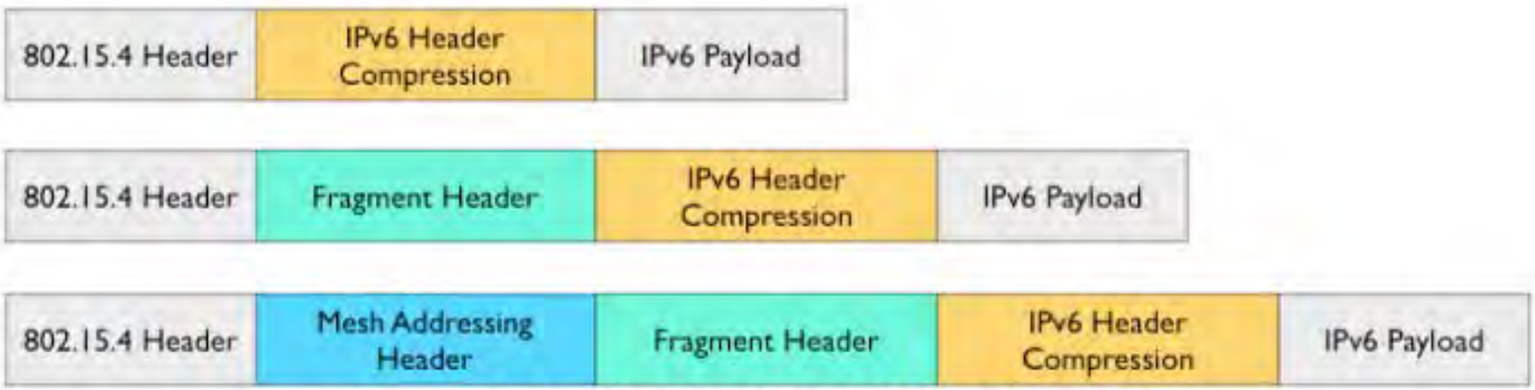
two categories of routing are defined: mesh-under or route-over. Mesh-under uses the layer-two (link layer) addresses (IEEE 802.15.4 MAC or short address) to forward data packets (the network is seen as a single IP SubNet); while route-over uses layer three (network layer) addresses (IP addresses). In the latter case the routing protocol is RPL.



In the storage free mode
It exploits source routing

Figure 5. Mesh-under and route-over packet forwarding

6LowPAN



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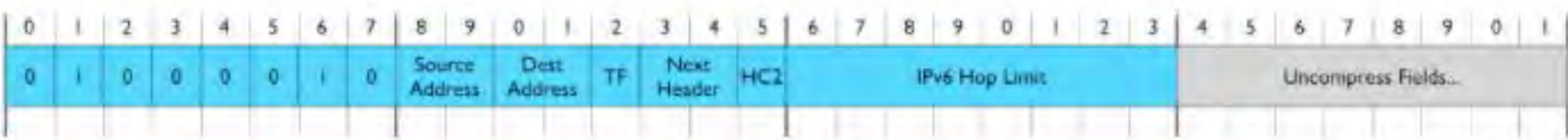
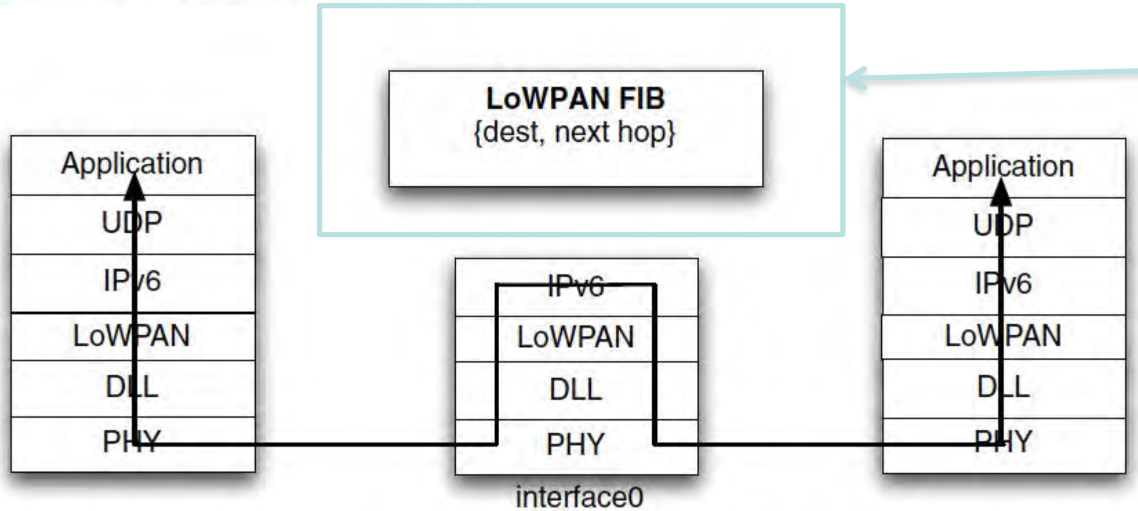


Figure 5. 6LoWPAN RFC 4944 IPv6 Header Compression.

6LoWPAN Routing



Updated by the Selected routing protocol

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

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

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

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)

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                   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_/
```

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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

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

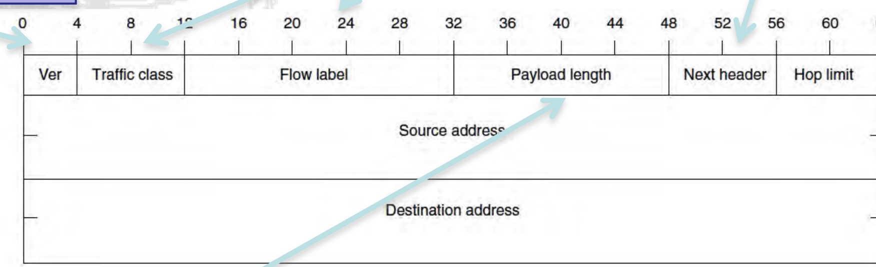
Often 0. C=1 means their values are zero

Always 6 not transmitted in HC1

Used to avoid transmitting First 64 bits of the address

```
 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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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

```
 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_/
```

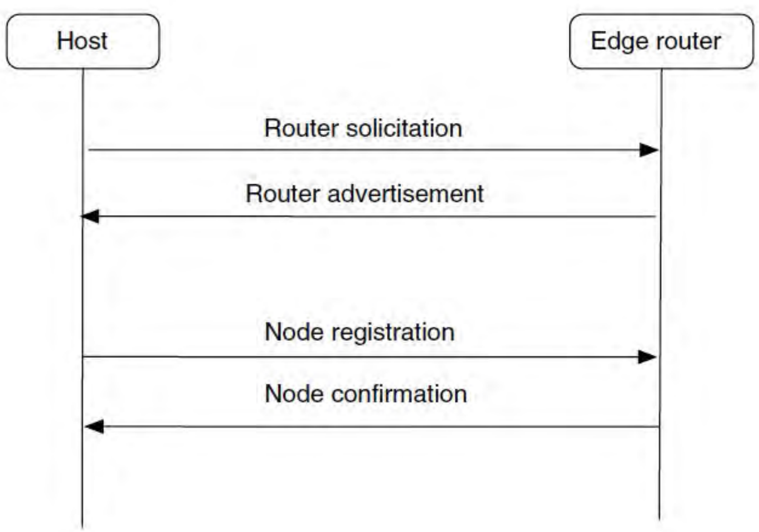
```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |1|S|D|L|_________| N.-C. fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch   _/ \_ HC1 header_/ \_ HC2 header_/
```

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

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        ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

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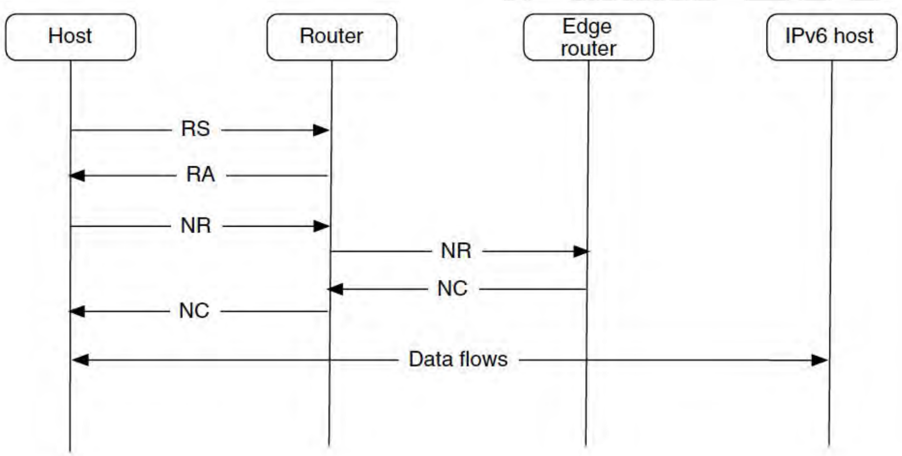
Bootstrapping an IoT network

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

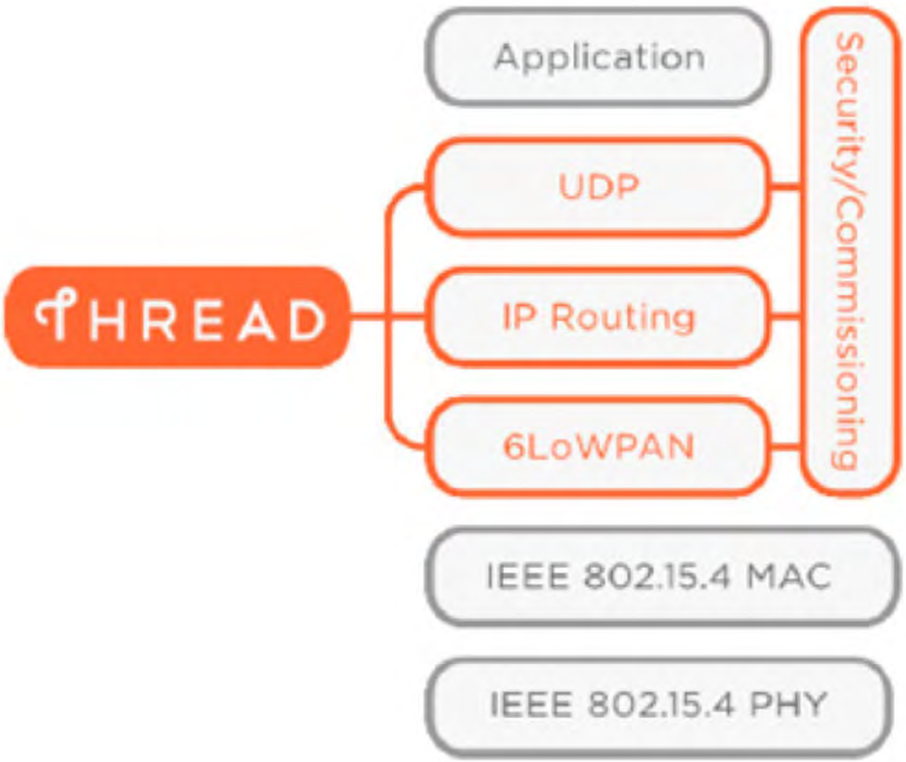


- Router solicitation (RS)
- Router advertisement (RA)
- Neighbor solicitation (NS)
- Neighbor advertisement (NA)

```
 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           ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Thread

To read:
https://www.threadgroup.org/Portals/0/documents/support/6LoWPANUsage_632_2.pdf



Standard-like routing Protocols for WSNs

Internet of Things a.a. 2019/2020

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

[†] *Department of Computer Science – University of Rome "Sapienza" – Italy*

Collection Tree Protocol
in Proceedings of ACM Sensys 2009
https://sing.stanford.edu/gnawali/ctp/sensys09-ctp.pdf
http://www.vs.inf.ethz.ch/publ/papers/santinis11_ctp-castalia_new.pdf

Omprakash Gnawali (Stanford University)

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Kyle Jamieson (University College London)

David Moss (People Power Company)

Philip Levis (Stanford University)

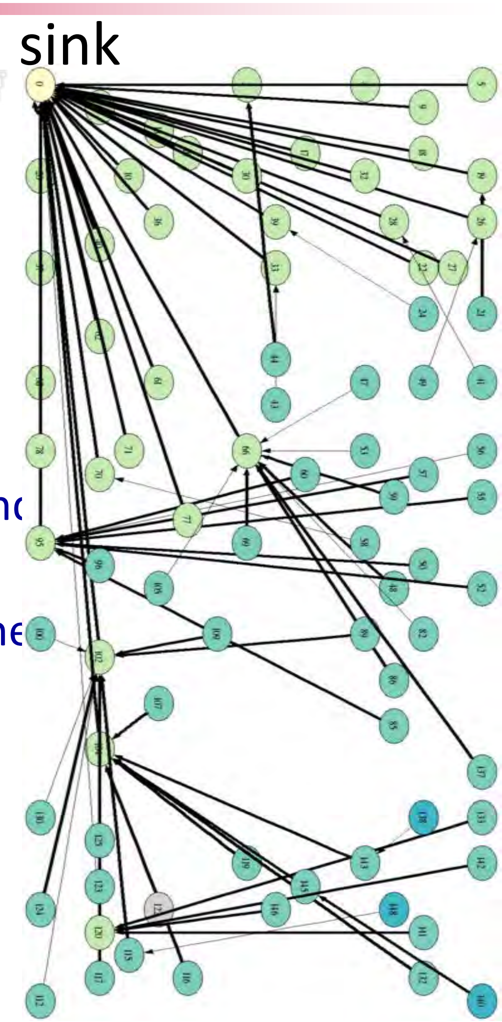
Slides partially taken from the presentation given by the authors at

ACM SenSys

November 4, 2009

Collection

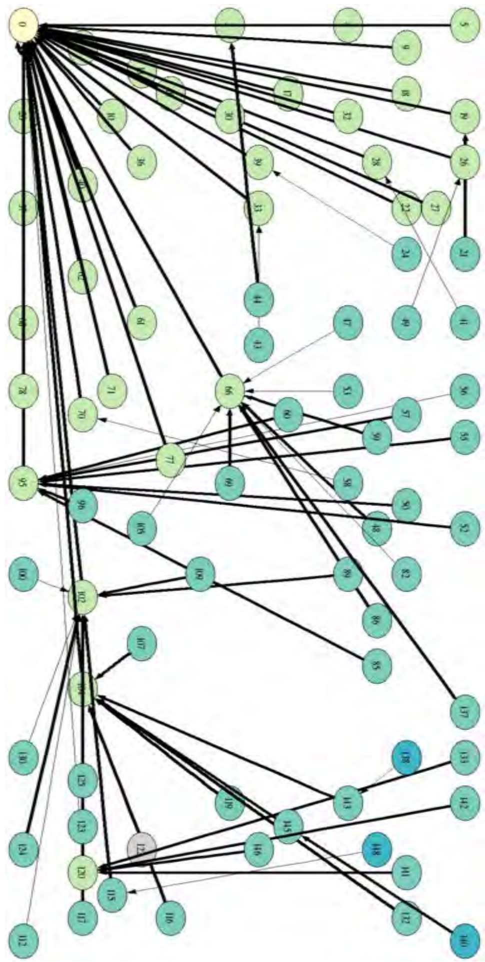
- Anycast route to the sink(s)
  - Used to collect data from the network to a small number of sinks (roots, base stations)
  - Each node selects one of its neighbors nodes as its parent
    - ✓ Parents handle packets received from the children and further forward them towards the sink
    - ✓ when there are multiple sinks, data are sent to the one with the minimum cost
- A distance vector protocol
  - Metric for selecting next hop:
    - ✓ Distance in hops from the sink
    - ✓ Quality of the local communication link



Desirable properties for collection tree protocol

- Reliability: a protocol should deliver at least 90% of end-to-end packets when a route exists
- Robustness: it should be able to operate without tuning or configuration in a wide range of network conditions;
- Energy Efficiency
- Hardware Independence

sink



Observation: link quality changes fast (even every 0,5s)

Common Architecture

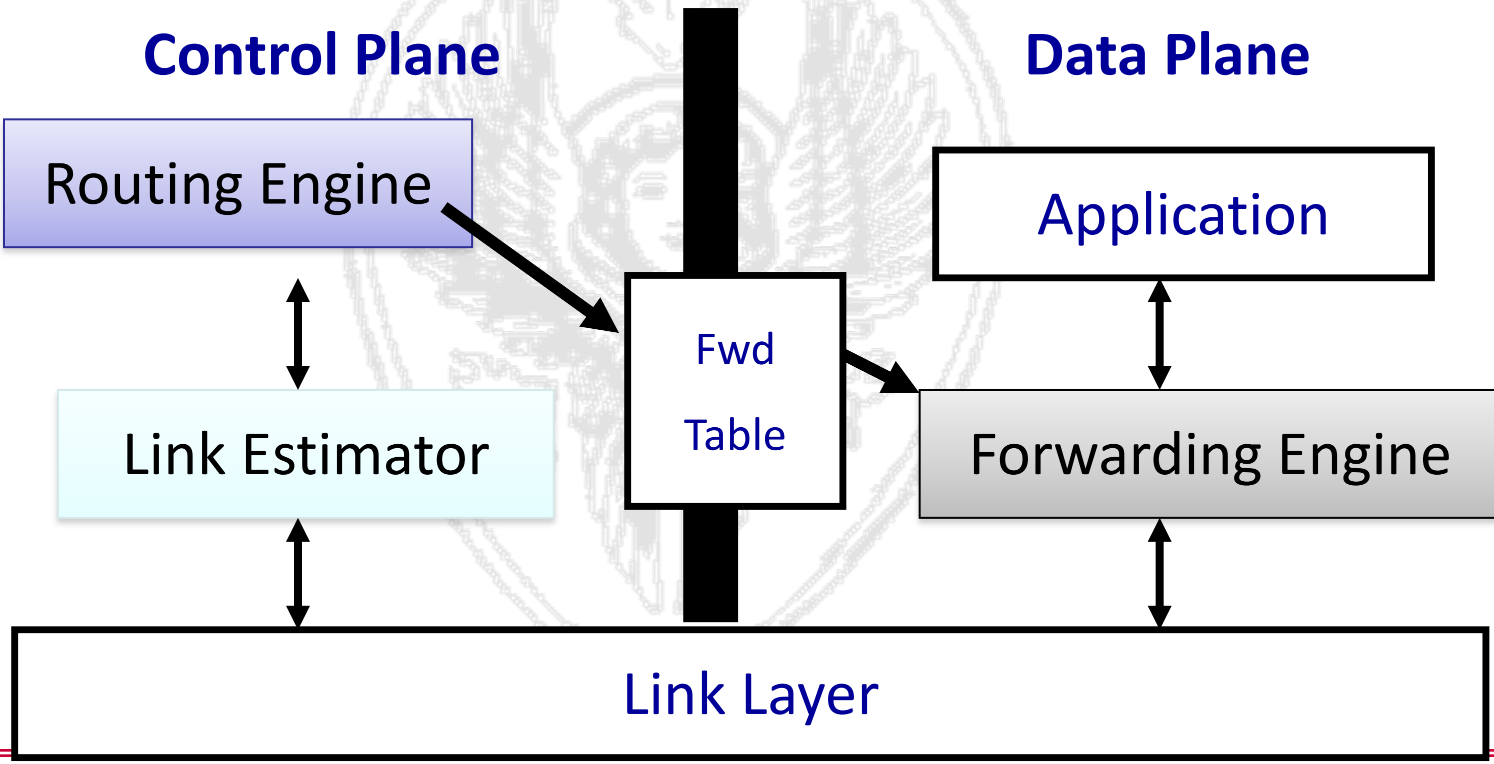
Sending and receiving beacons

for route construction and maintenance

Creating and updating the routing table

Perform forwarding

Detect and Repair Loops, filter duplicate packets



Parent selection metric

- ETX = Expected Number of Transmissions to reach the sink
- Computed based on performance experienced in the recent past by beacon and data packets for the local 1-hop ETX_{loc}

$$Q_u = \frac{n_u}{n_a}. \qquad Q_b[k] = \alpha_b \frac{n_b}{N_b} + (1 - \alpha_b) Q_b[k-1].$$

- ETX_{mhp} via a given neighbor computed as the sum of the ETX_{loc} and of the estimated ETX_{mhp} at that neighbor

Number of bits needed
To tx successfully Nb ones

Parent selected only among uncongested nodes

Paren

Pull bit

- ETX = Expected Number of Tra

Congested bit

- Comput[e] ... forma past by beacon and data packe

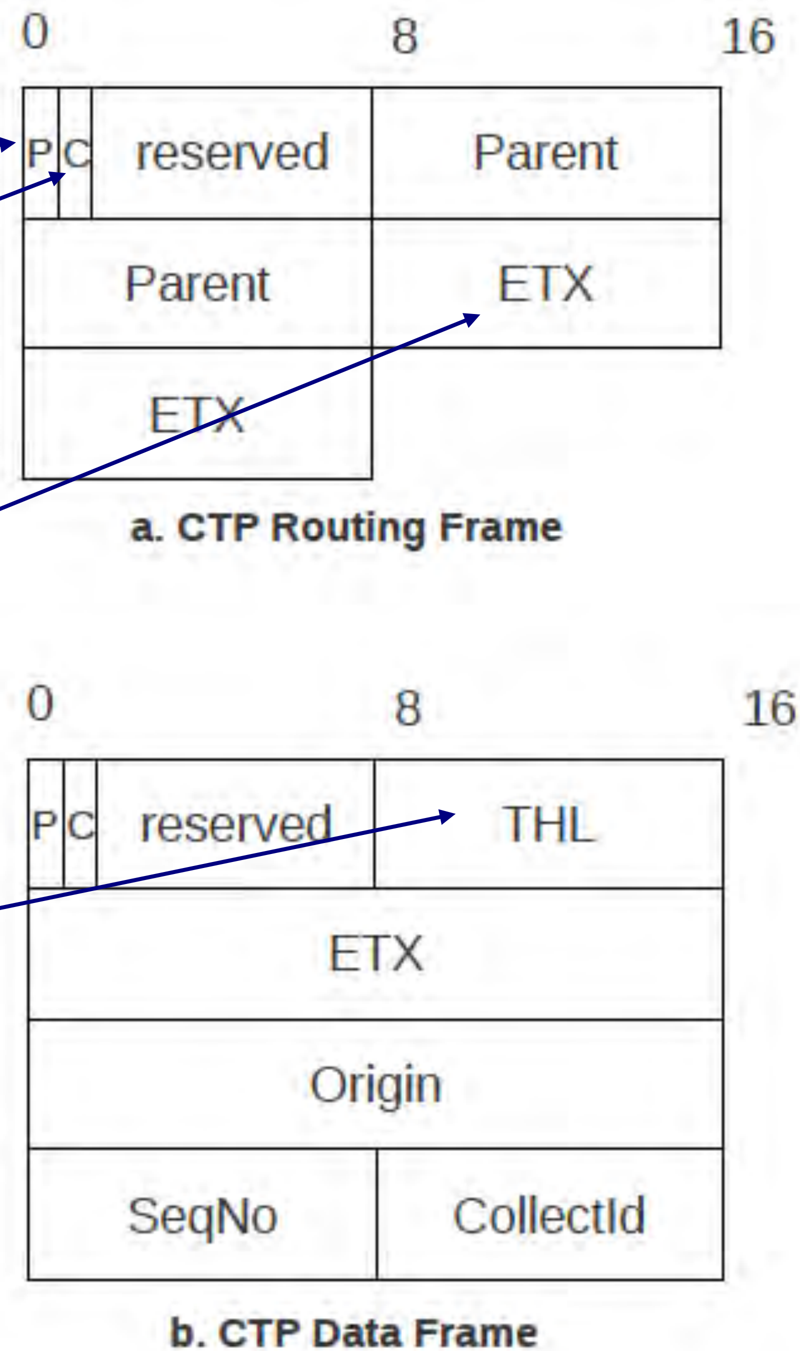
$$Q_u = \frac{n_u}{n_a}.$$

Routing cost

- ETX_{mhp} via a given neighbor co ETX_{loc} and of the estimated ETX at that neigh

Time has lived

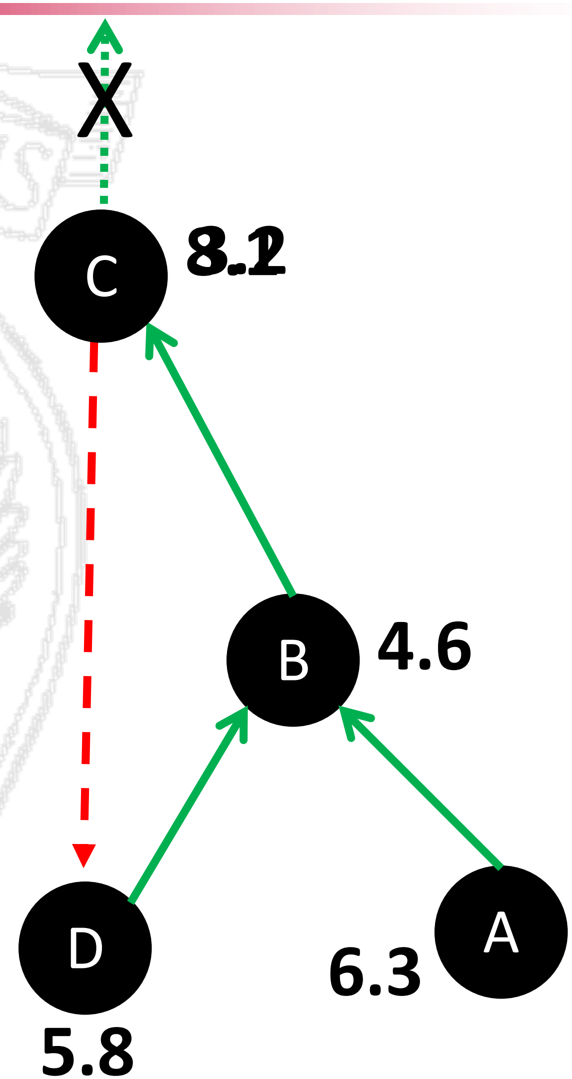
Parent selected only amor



Routing Loops

– Cost does not decrease

Parent selected as the neighbor with lowest cost

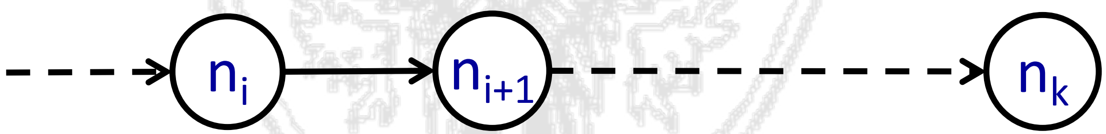


Routing Consistency

- *Next hop* should be closer to the destination
- Maintain this consistency criteria on a path

$$\forall i \in \{0, k-1\},\ ETX(n_i) > ETX(n_{i+1})$$

- Inconsistency due to stale state



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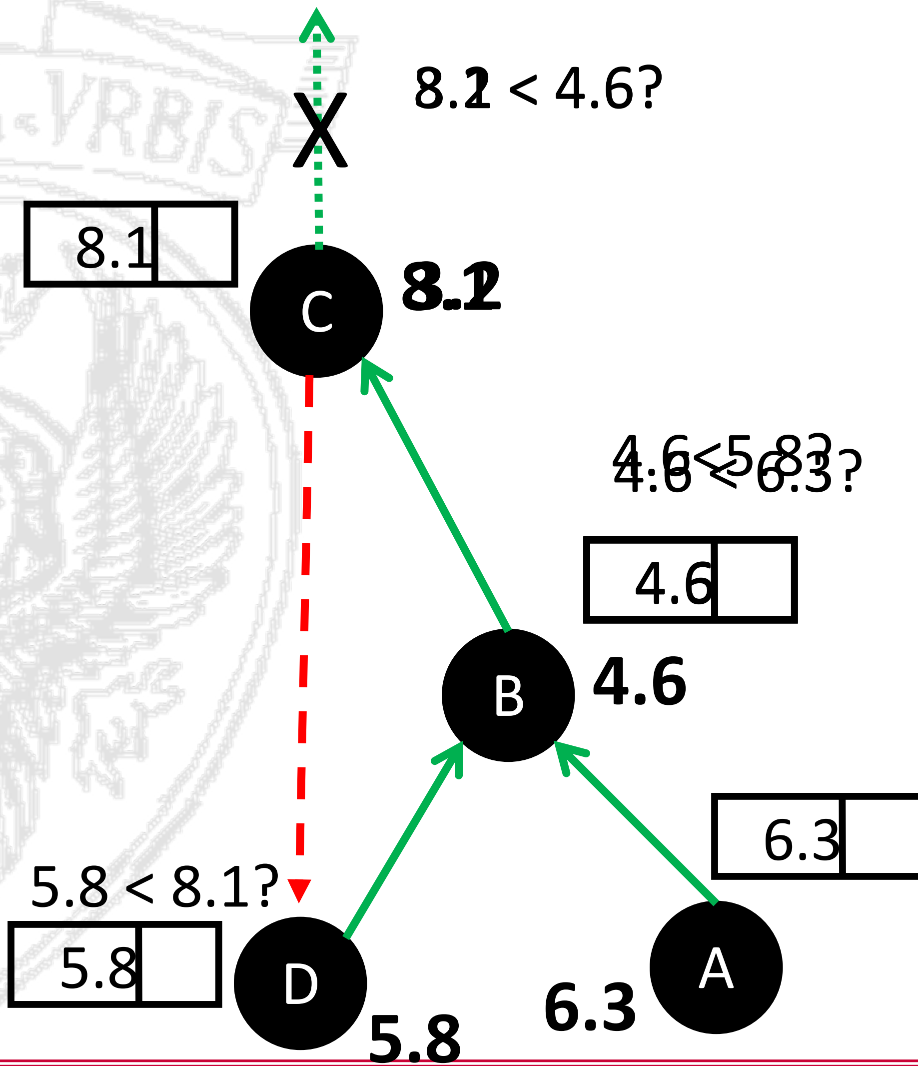
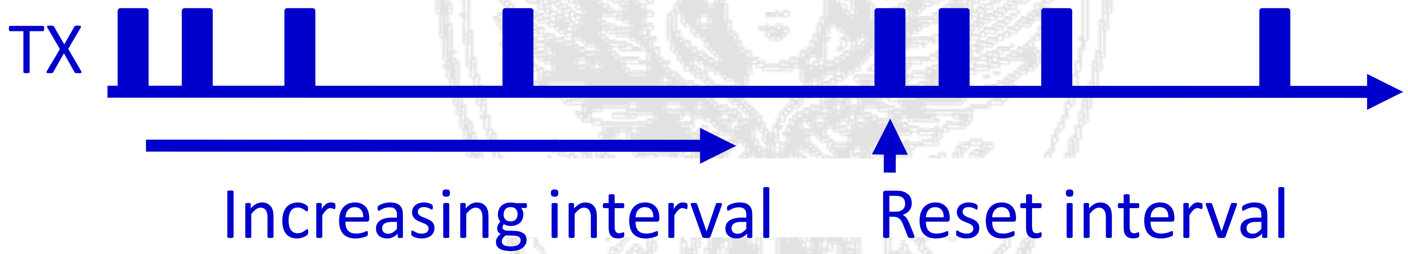
Detecting Routing Loops

- Datapath validation
  - Cost in the packet
  - Receiver checks
- Inconsistency
  - Larger cost than on the packet
- On Inconsistency
  - Don't drop the packets
  - Signal the control plane



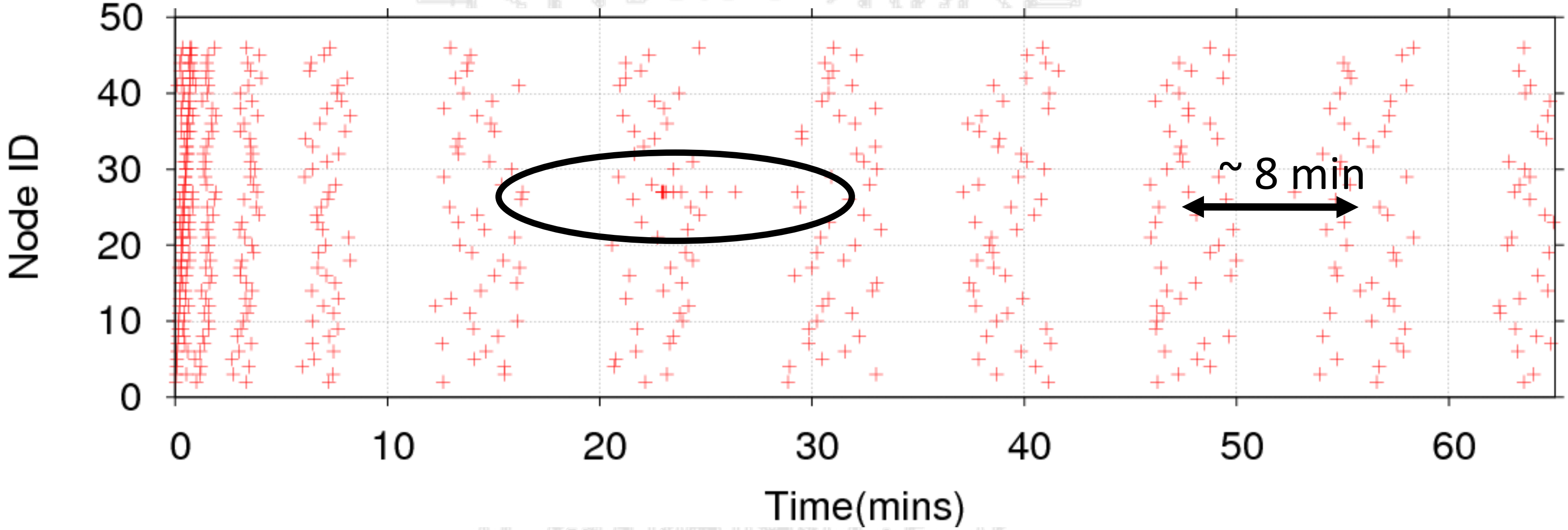
Control Traffic Timing

- Extend Trickle to time routing beacons
- Reset the interval
  - ✓ ETX(receiver) >= ETX(sender)
  - ✓ Significant decrease in gradient
  - ✓ "Pull" bit



Control propagation rate
- Start with a small interval
- Double the interval up to some max
- Reset to the small interval when inconsistency identified

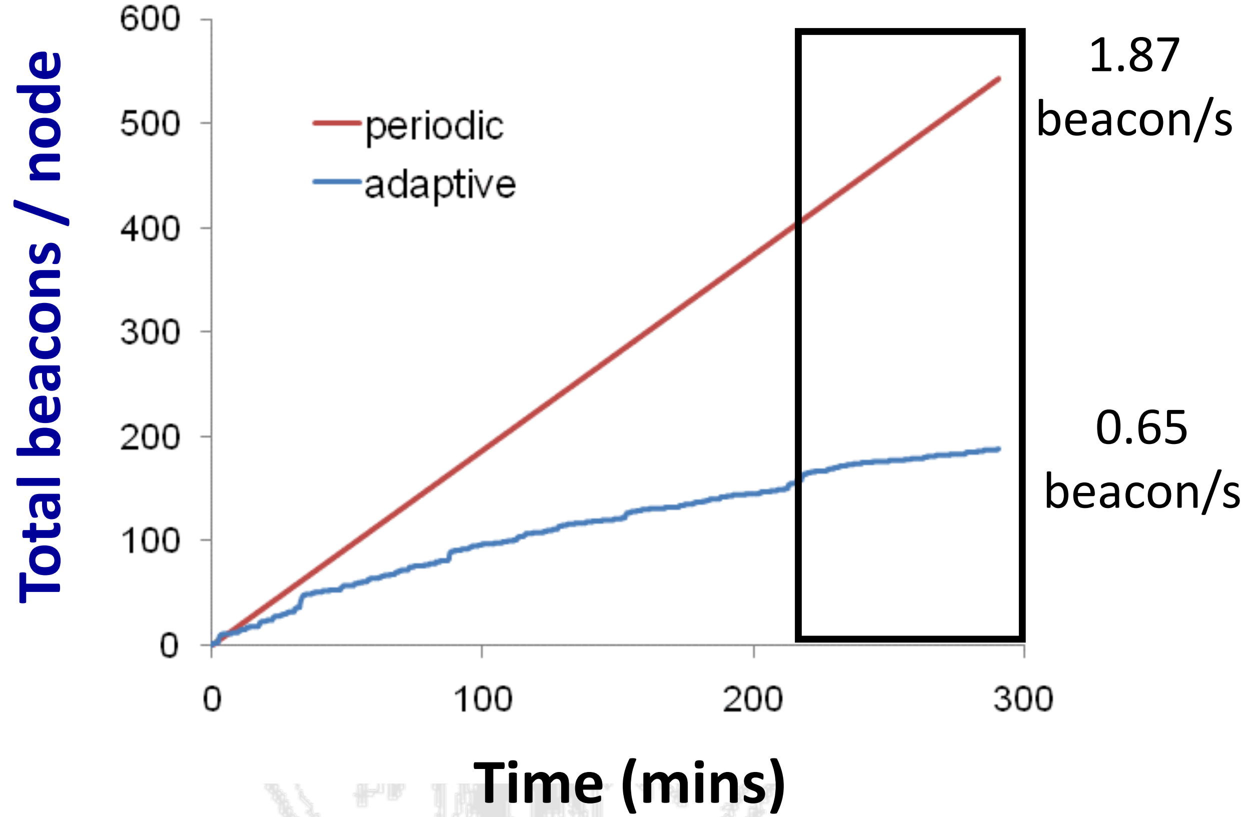
Adaptive Beacon Timing



Tutornet

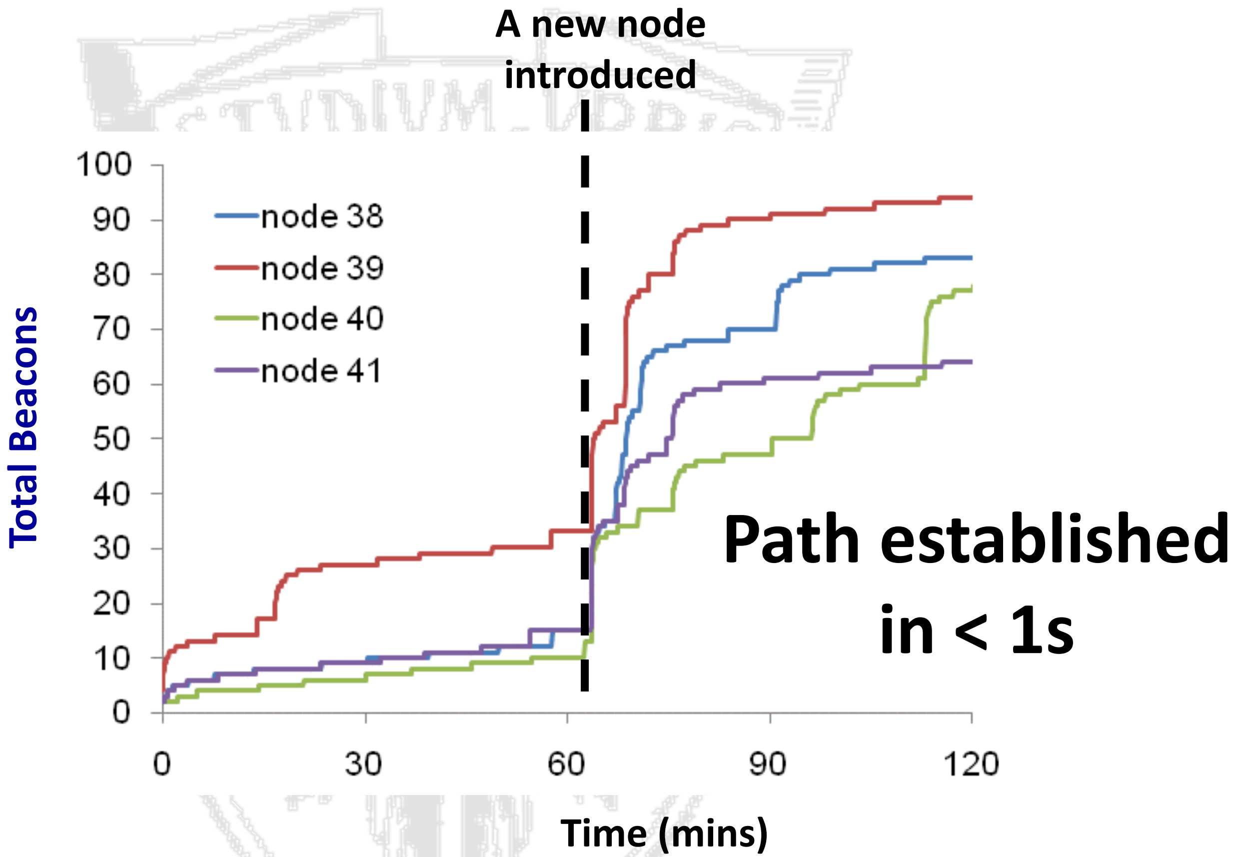
Infrequent beacons in the long run

Adaptive vs Periodic Beacons



Tutornet

Less overhead compared to 30s-periodic



Tutornet

Efficient and agile at the same time

Experiments

- 12 testbeds
- 20-310 nodes
- 7 hardware platforms
- 4 radio technologies
- 6 link layers

Testbed	Platform	Nodes	Physical size m^2 or m^3
Tutornet	Tmote	91	50×25×10
Wymanpark	Tmote	47	80×10
Motelab	Tmote	131	40×20×15
Kansei	TelosB	310	40×20
Mirage	Mica2dot	35	50×20
NetEye	Tmote	125	6×4
Mirage	MicaZ	86	50×20
Quanto	Epic-Quanto	49	35×30
Twist	Tmote	100	30×13×17
Twist	eyesIFXv2	102	30×13×17
Vinelab	Tmote	48	60×30
Blaze	Blaze	20	30×30

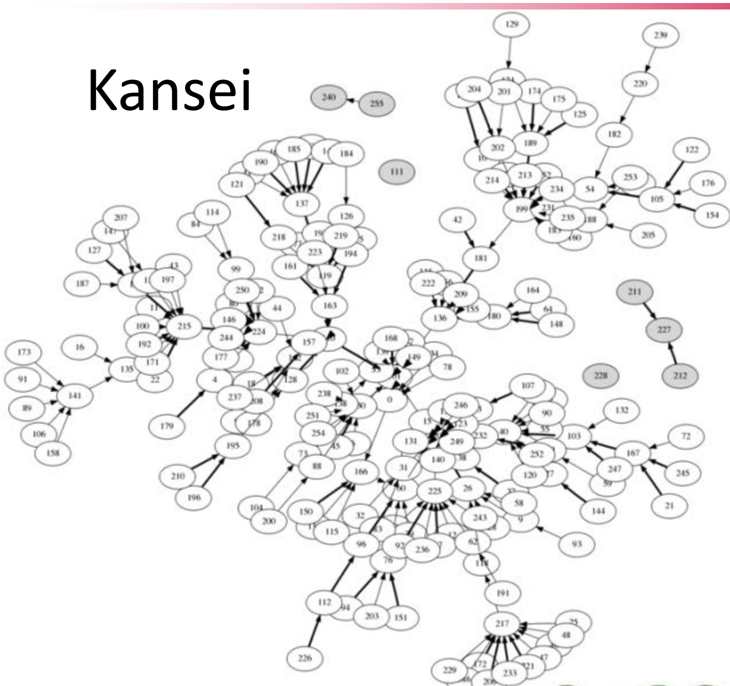
Variations in hardware, software, RF environment, and topology

Evaluation Goals

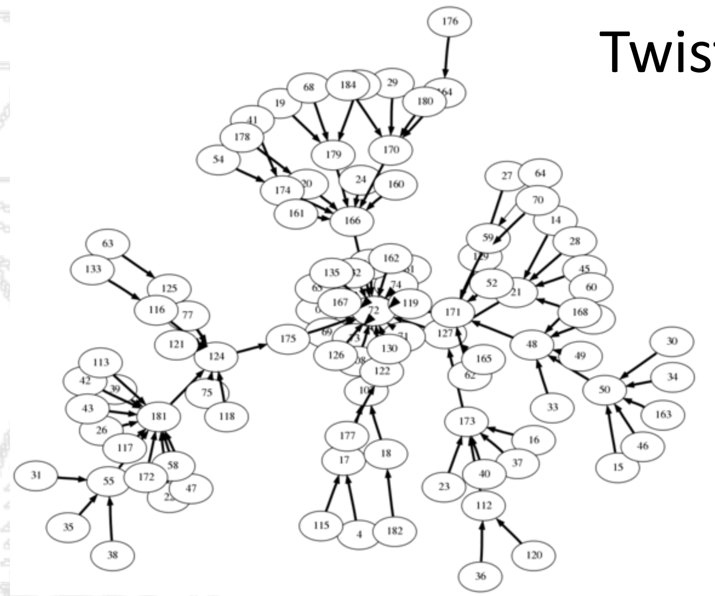
- Reliable?
  - Packets delivered to the sink
- Efficient?
  - TX required per packet delivery
- Robust?
  - Performance with disruption

CTP Noe Trees

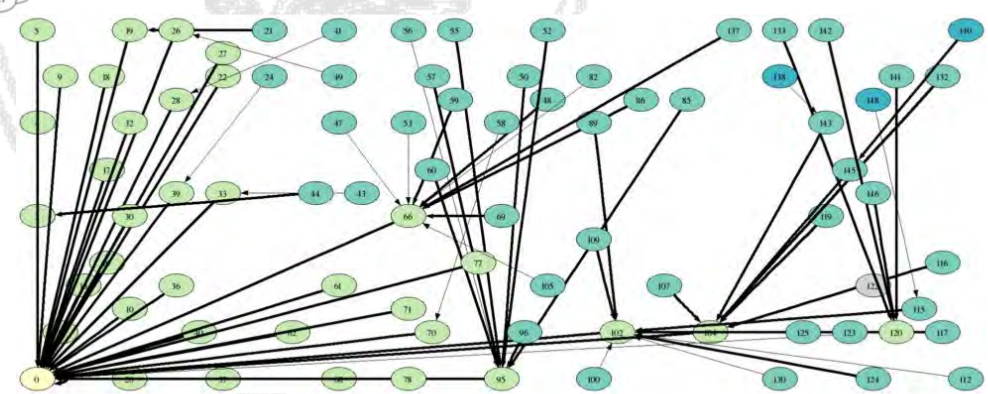
Kansei

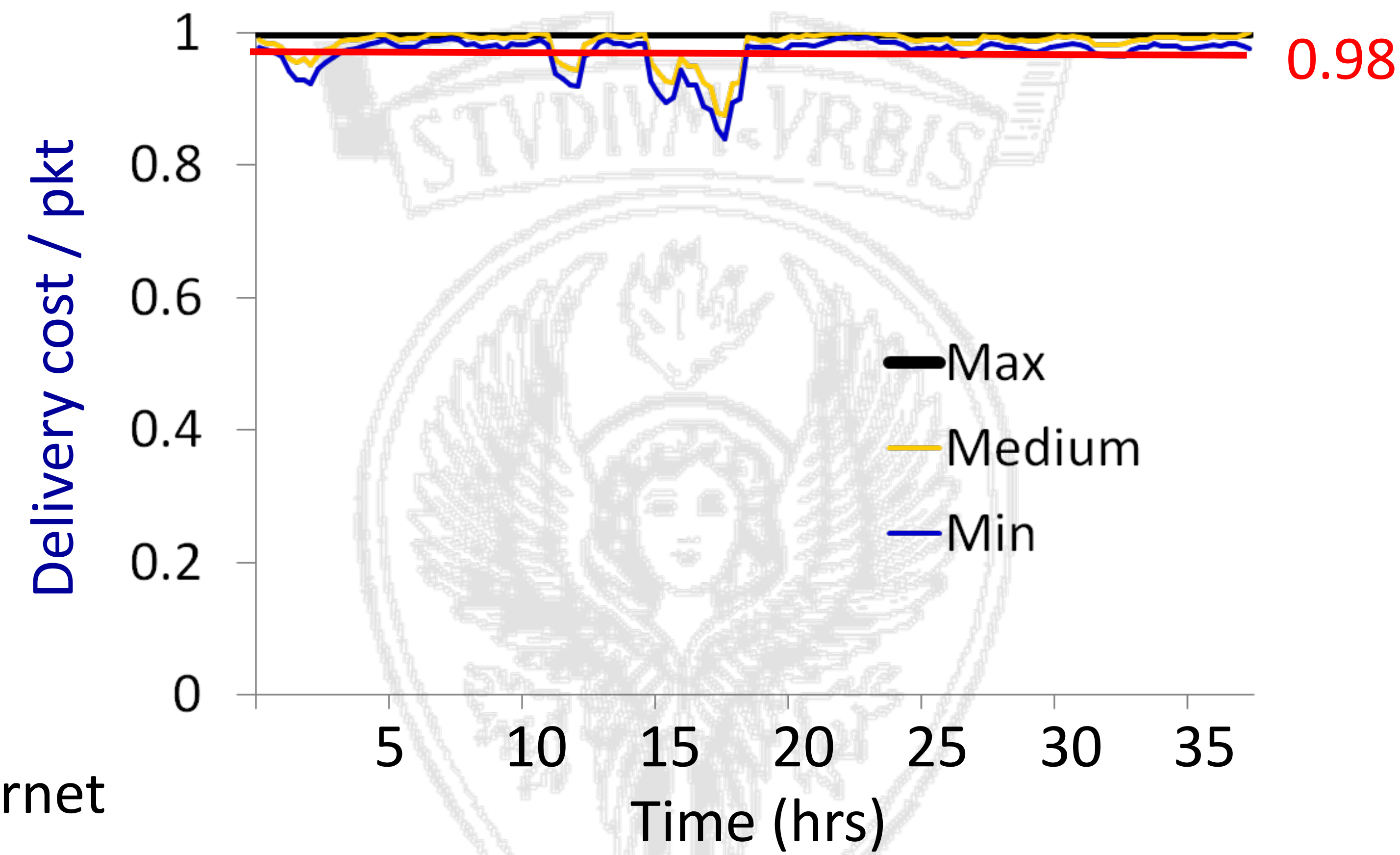


Twist



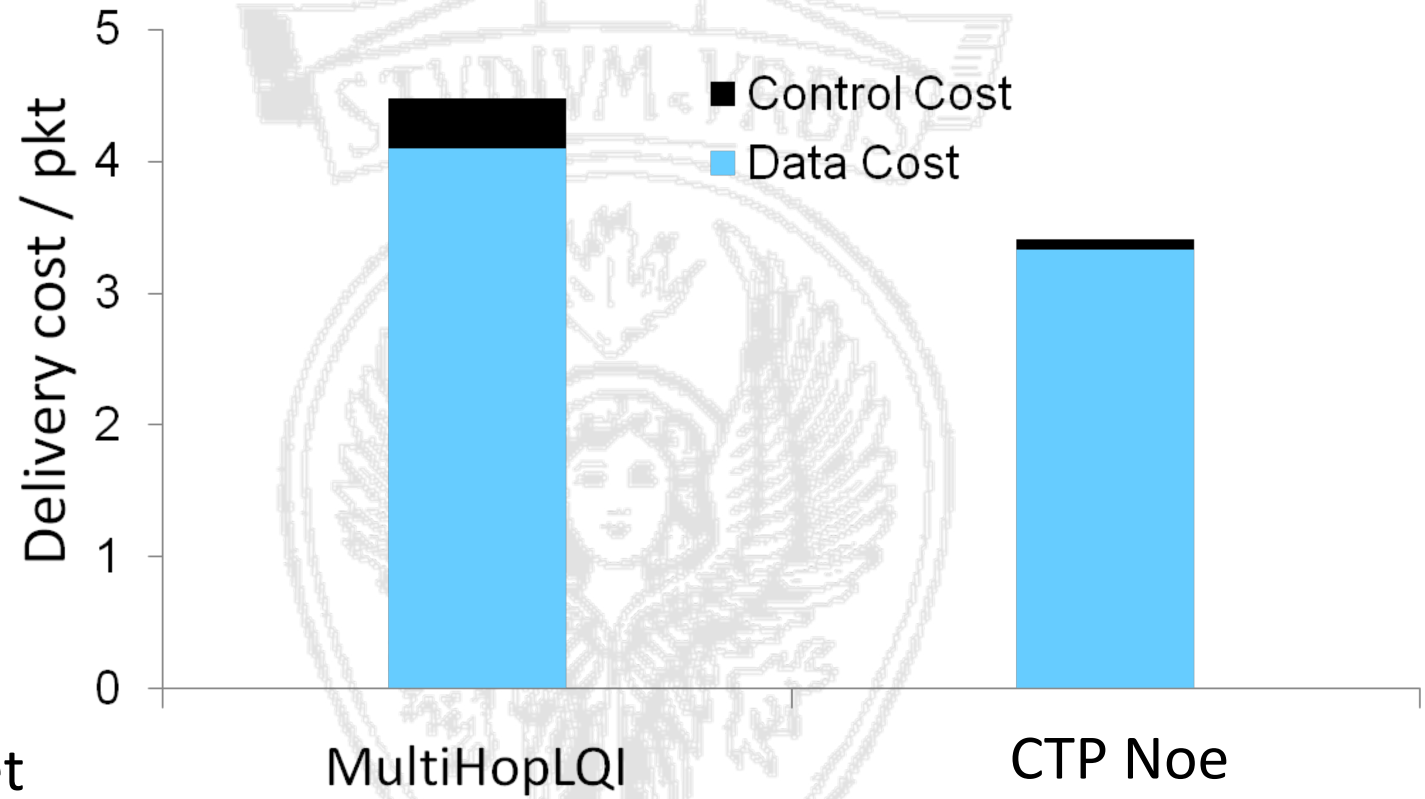
Mirage





Tutornet

High delivery ratio across time
(short experiments can be misleading!)

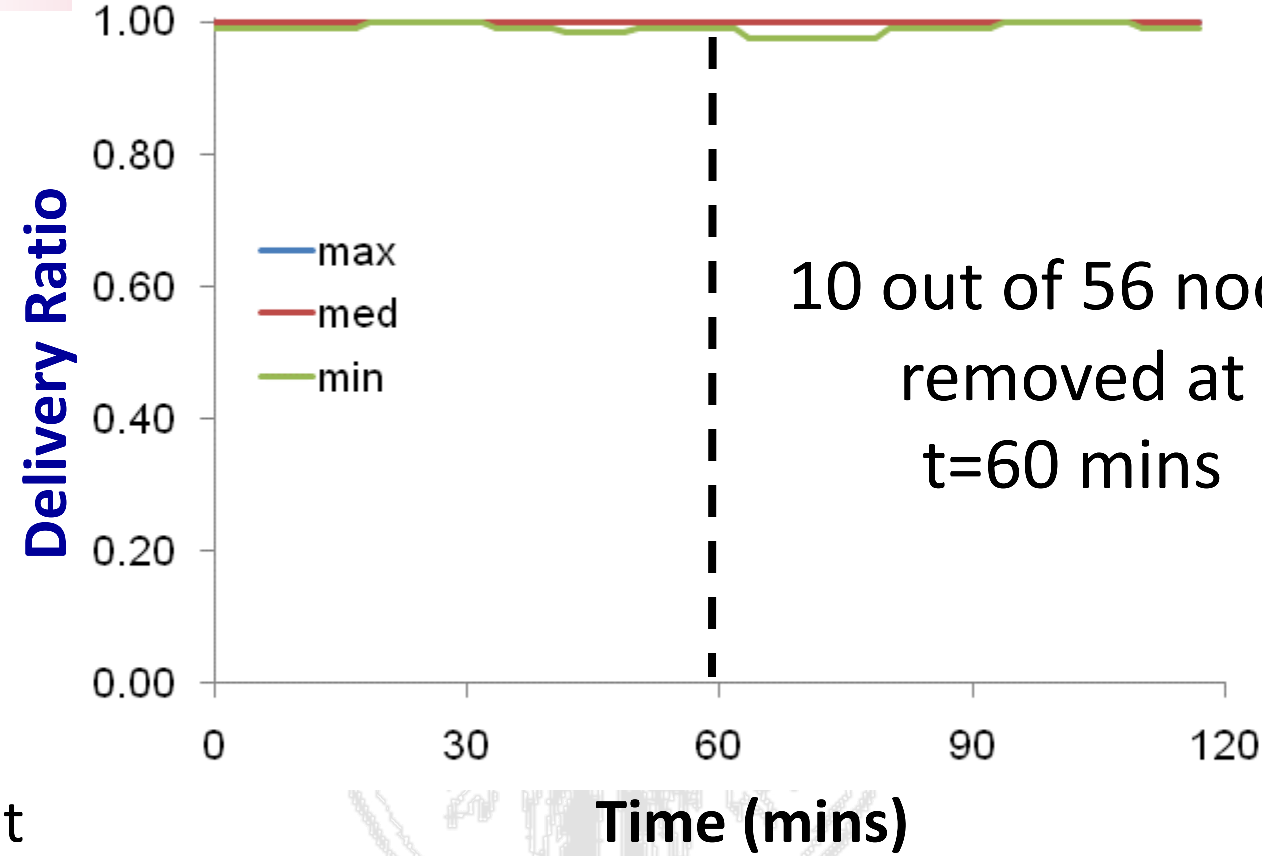


Tutornet

Low data and control cost

Link Layer	Average Delivery	PL	Cost	$\frac{\text{Cost}}{\text{PL}}$	Duty Cycle Median	Duty Cycle Mean
CSMA	94.7%	3.05	5.53	1.81	100.0%	100%
BoX-50ms	94.4%	3.28	6.48	1.98	24.8%	24.9%
BoX-500ms	97.1%	3.38	6.61	1.96	4.0%	4.6%
BoX-1s	95.1%	5.40	8.34	1.54	2.8%	3.8%
LPP-500ms	90.5%	3.76	8.55	2.27	6.6%	6.6%

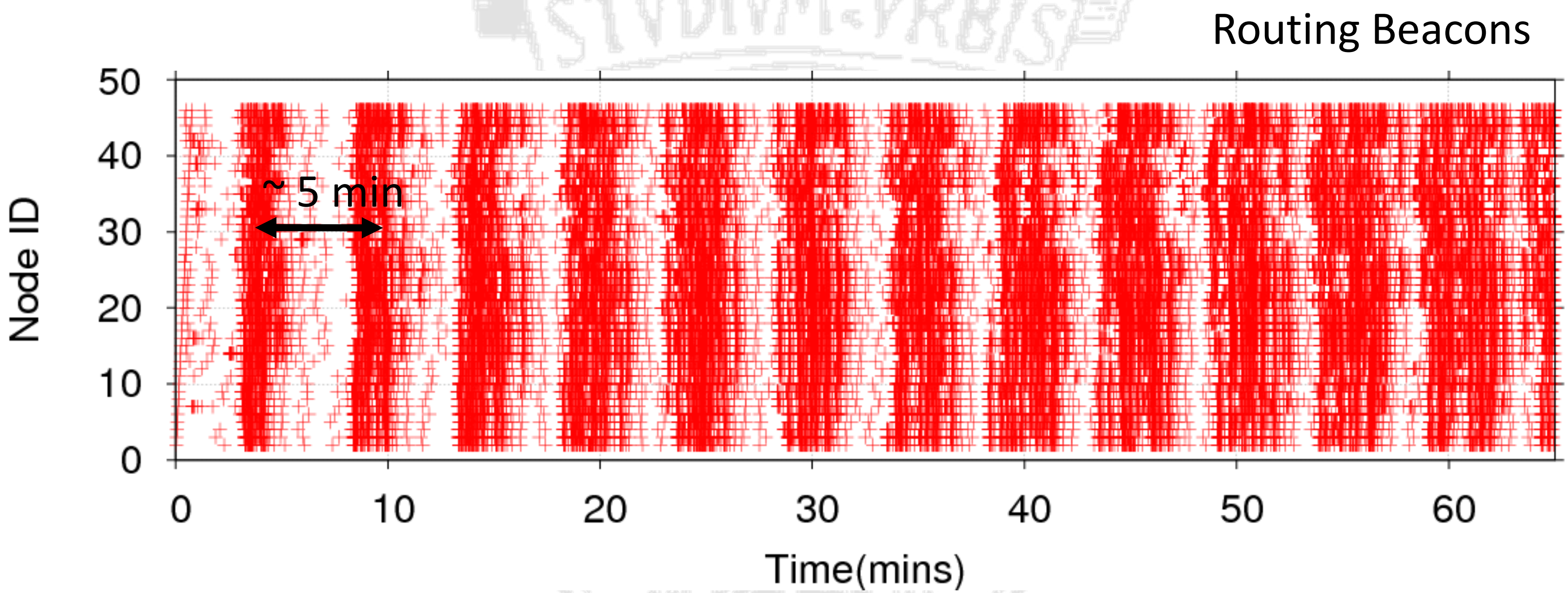
Low duty-cycle with low-power MACs



Tutornet

No disruption in packet delivery

Nodes reboot every 5 mins



Tutornet

Delivery Ratio > 0.99

High delivery ratio despite serious network-wide disruption (most loss due to reboot while buffering packet)