MAC Protocols for sensing systems

Internet of Things a.a. 2021/2022

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

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

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Energy-efficient MAC protocols

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S-MAC (Sensor MAC)

W. Ye, J. Heidemann, D. Estrin "An energy efficient MAC Protocol for Wireless Sensor Networks", IEEE Infocom 2002

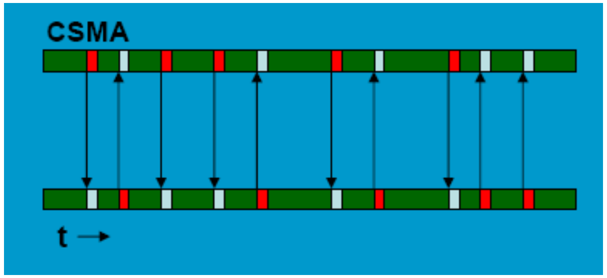
https://www.isi.edu/~johnh/PAPERS/Ye02a.pdf

Synchronized MAC based on duty cycle

Performance objectives

1) Energy efficiency

- Sources of energy waste
  - *collision*. When a transmitted packet is corrupted it has to be discarded, and the follow-on retransmissions increase energy consumption. Collisions also increase latency.
  - *overhearing*, meaning that a node picks up packets that are addressed to other nodes.
  - *control packet overhead*
  - *idle listening*, *i.e.*, listening to receive possible traffic that is not sent (major source of energy consumption).



2) End-to-end latency

3) Fairness

4) Network capacity/scalability (to density and traffic)

Nodes sleeping scheme

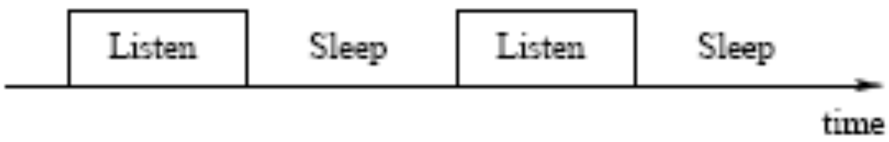


Fig. 1. Periodic listen and sleep.

- Nodes follow an awake/asleep schedule with a given duty cycle d
- In S-MAC nodes schedule are synchronized
  - all nodes transmit in the same slot and receive in the same slot if possible **(WHICH ARE THE PROS? WHICH ARE THE CONS?)**

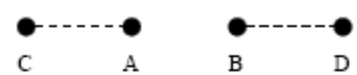


Fig. 2. Neighboring nodes A and B have different schedules. They synchronize with nodes C and D respectively.

  - Periodic exhange of information is needed to resynch in case of clock drifts (if resynch every few tens seconds drifts remain limited)

Choosing and maintaining schedules

- Before a node starts its periodic «listen and sleep» activity, it needs to choose a schedule and broadcast it to its immediate neighbors (schedule exchange).
  - at start up node x listens for some random time
    - ✓ if x receives a SYN from another node y, it synchronizes to its schedule (x is a *follower*). It waits for a random delay t_d and rebroadcasts its schedule.
      - follower of the same synchronizer do not collide (or collide with low prob) thanks to t_d
    - ✓ otherwise node x selects a random time T to sleep before waking up again and sends this value T to neighbors in a SYN (x therefore becomes a *synchronizer*)
    - ✓ if a node receives a different schedule after it selects its own, which is followed by more than one device, it adopts both schedules, broadcasting the new one
      - "border nodes" where two synch waves meet are the ones with multiple schedules
        - » they consume more energy
- Each node also maintains a *schedule table* that stores the schedules of all its known neighbors.

When a node has a packet to send …

- It waits for the destination to be ON and sends the packet following CSMA/CA
  - performs carrier sense for a random interval
  - if no transmission within this interval the floor is taken (physical carrier sense) to transmit RTS/CTS
  - if the RTS/CTS is successful (virtual carrier sensing) DATA is sent which is followed by an ACK
  - NAVs are used for deciding for how long nodes should go to sleep before they can try to access again in case neighbors are transmitting
  - to better exploit the time needed to hanshake (RTS/CTS) bursts of packets are transmitted if more packets are in queue for the same destination
    - ✓ Limited packet size and transmission of ACKs following reception avoids hidden terminal problem if nodes waking up wait for some limited time before transmitting

Maintaining synchronization

- Some initially exchanged SYN maybe lost e.g. due to collision, or new nodes maybe added
- Clock drifts

How do we keep nodes schedules up to date and synchronized?

- A node periodically sends a SYN.
- For nodes to receive SYN and DATA listen times are divided into two intervals

Maintaining synchronization

- Some initially exchanged SYN maybe lost e.g. due to collision, (
- Clock dri

How do we … and synchroni…

- A node p
- For node … times are divided in

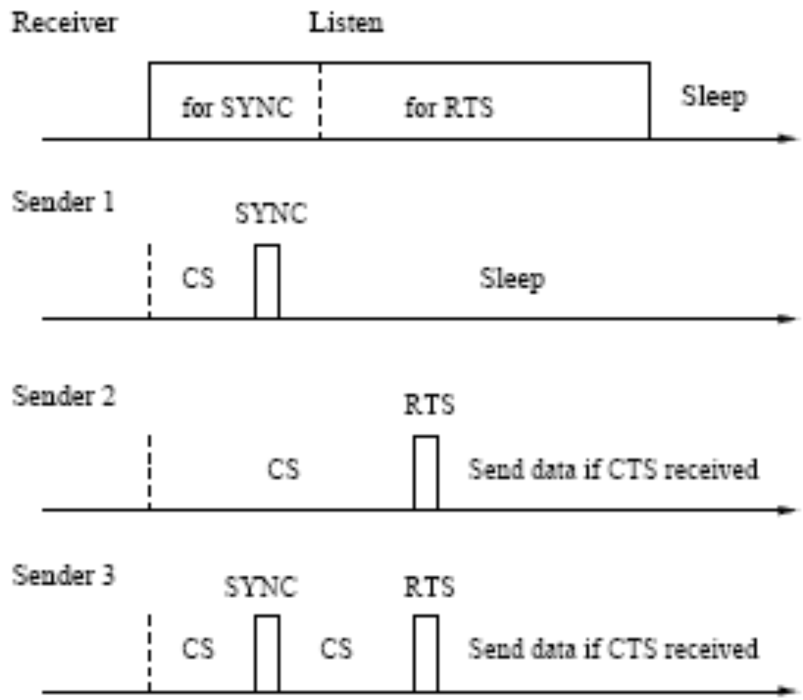


Fig. 3. Timing relationship between a receiver and different senders. CS stands for carrier sense.

S-MAC: Limits

- Needs synchronization
  - even if clock drifts are not a major problem synchronization adds control overhead which may impair long lifetimes (e.g., in those applications where communication needs are sporadic)
- Throughput is reduced since only the active part of the frame is used for communication
  - It is further reduced because tx/rx occur only during scheduled ON times (that are all synchronized)
- Latency increases since when a node generates a packet it has to wait for the next hop relay on time before the packet can be forwarded.

T-MAC (Timeout MAC)

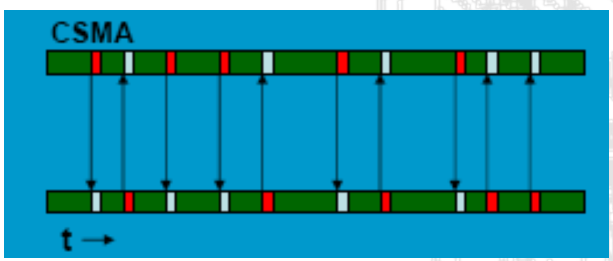
Tijs van Dam, Koen Langendoen "An adaptive energy efficient MAC Protocol for Wireless Sensor Networks", ACM SenSys 2003

https://courses.cs.washington.edu/courses/cse590l/04wi/papers/dam-adaptive.pdf

Synchronized MAC based on duty cycle

T-MAC

- Observation: In SMAC there are two critical parameters (the active time and the frame time)
  - a long frame time increases latency
  - given an active time the longer the frame time the lower the energy consumption
  - the active time should be dimensioned based on traffic: for a frame time the higher the traffic, the longer the active time should be



  - In SMAC the two parameters are fixed
    - ✓ setting should depend on worst case
  - in TMAC the frame time is fixed but the active time is dynamically adapted

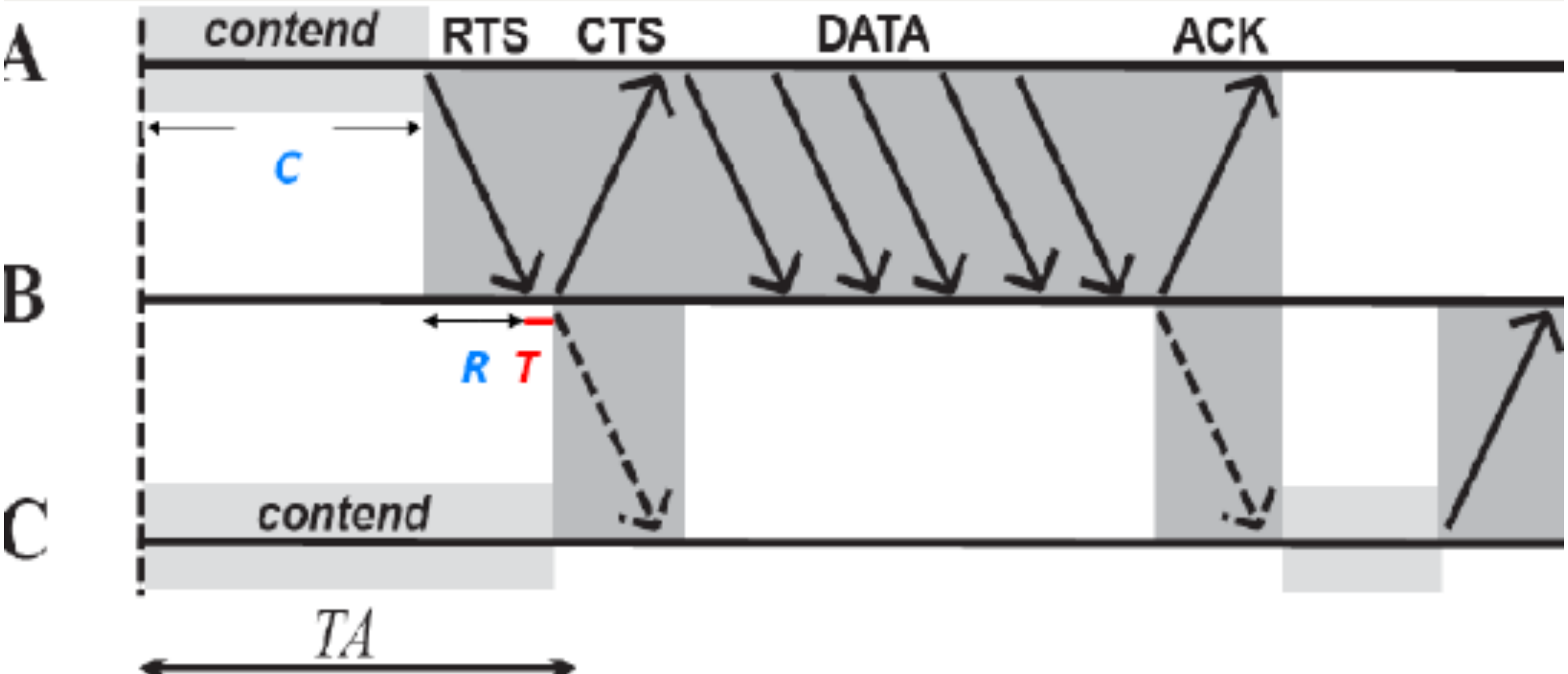
T-MAC

- Nodes synchronize their schedules using the SMAC virtual clustering approach.
- Within an active time CSMA/CA + back to back packet transmission in bursts are adopted
- Changes from S-MAC: if no transmission from neighbors for a time TA the active time is aborted and node goes to sleep

- TA timer is reset if: a) any data is received on the radio,b) communication (e.g, collision) is sensed on the radio, c) data are transmitted, d) RTS/CTS are exchanged by neighbors
  - ✓ A node should not go to sleep while its neighbors are still communicating since it maybe the receiver of a subsequent message

How to determine TA

Determining of TA



- TA > C+R+T (must be long enough to receive at least the start of the CTS packet)

T-MAC

- other changes from SMAC:
  - When a node sends an RTS but does not receive a CTS back this may be due to one of the following events:
    - ✓ 1) the RTS was not received due to collisions
    - ✓ 2) the receiving node cannot answer due to an RTS/CTS overheard
    - ✓ 3) the receiving node is sleeping

    In cases 1-2) reducing the active time would be wrong
      - " a node should retry by resending the RTS at least twice before giving up and going to sleep"
  - early sleep may degrade throughput (while decreasing idle listening and energy consumption)
    - ✓ mechanisms introduced to signal to nodes there is traffic for them at the beginning of the active time to prevent them from going to sleep

Early sleep problem

Data gathering at the sink

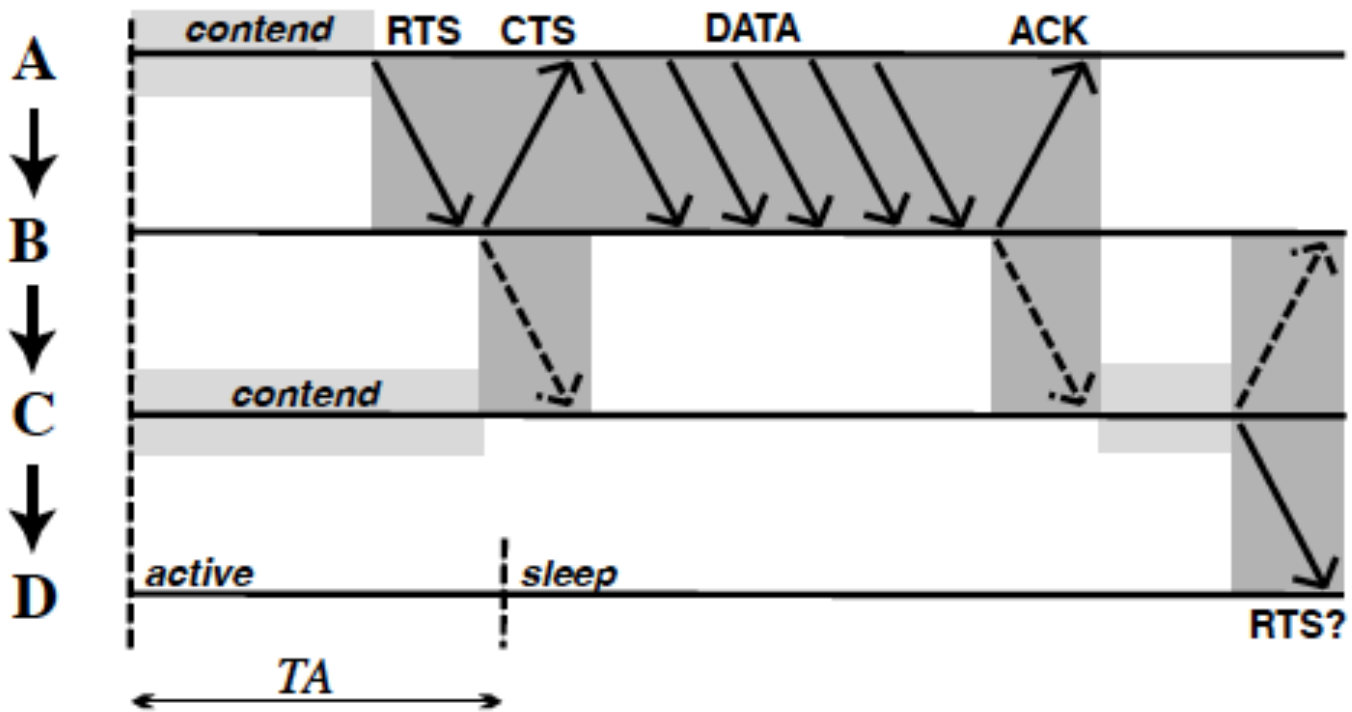


Figure 4: The *early sleeping* problem. Node D goes to sleep before C can send an RTS to it.

Early sleep- Solution 1

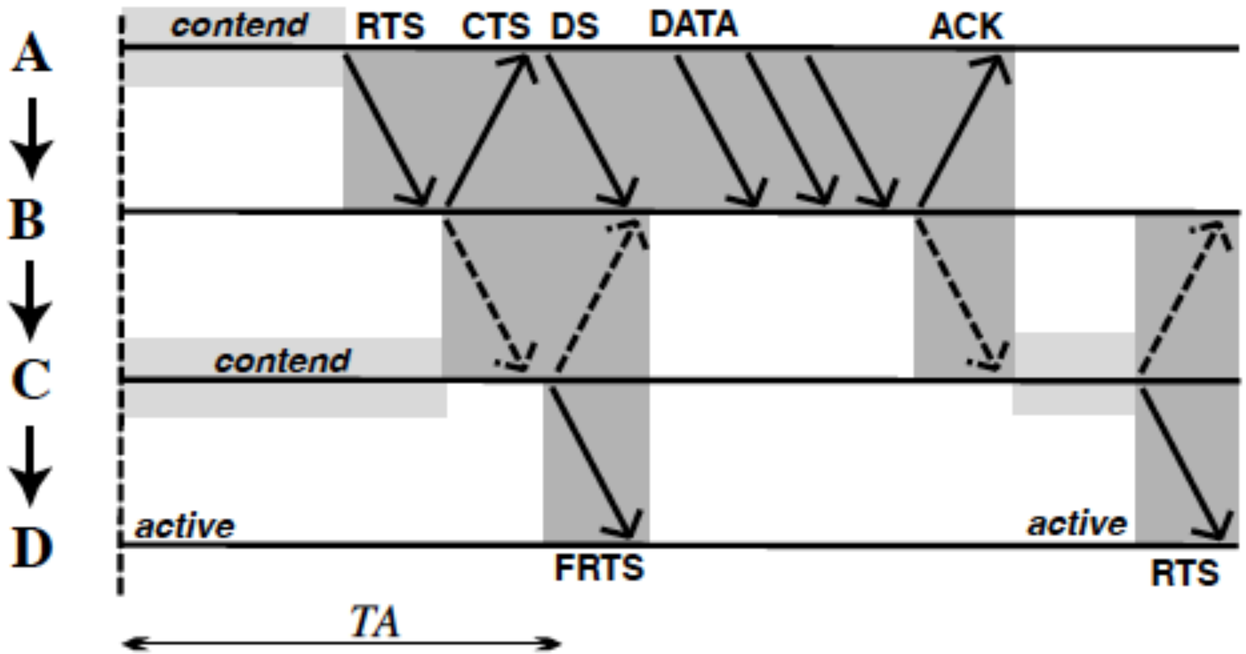


Figure 5: The future-request-to-send packet exchange keeps Node D awake.

The sender must wait before transmitting the real data that a FRTS is received. To maintain the channel floor in the meanwhile it transmits a dummy DS (Data Send) packet

Early sleep- Solution 2

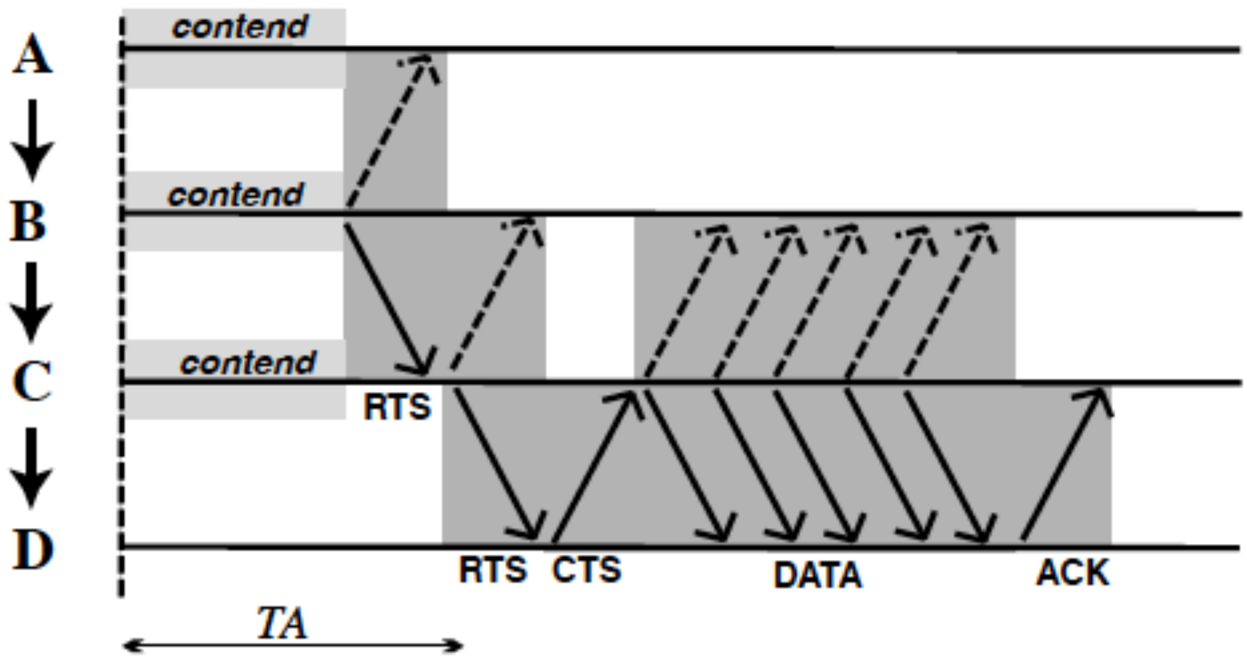
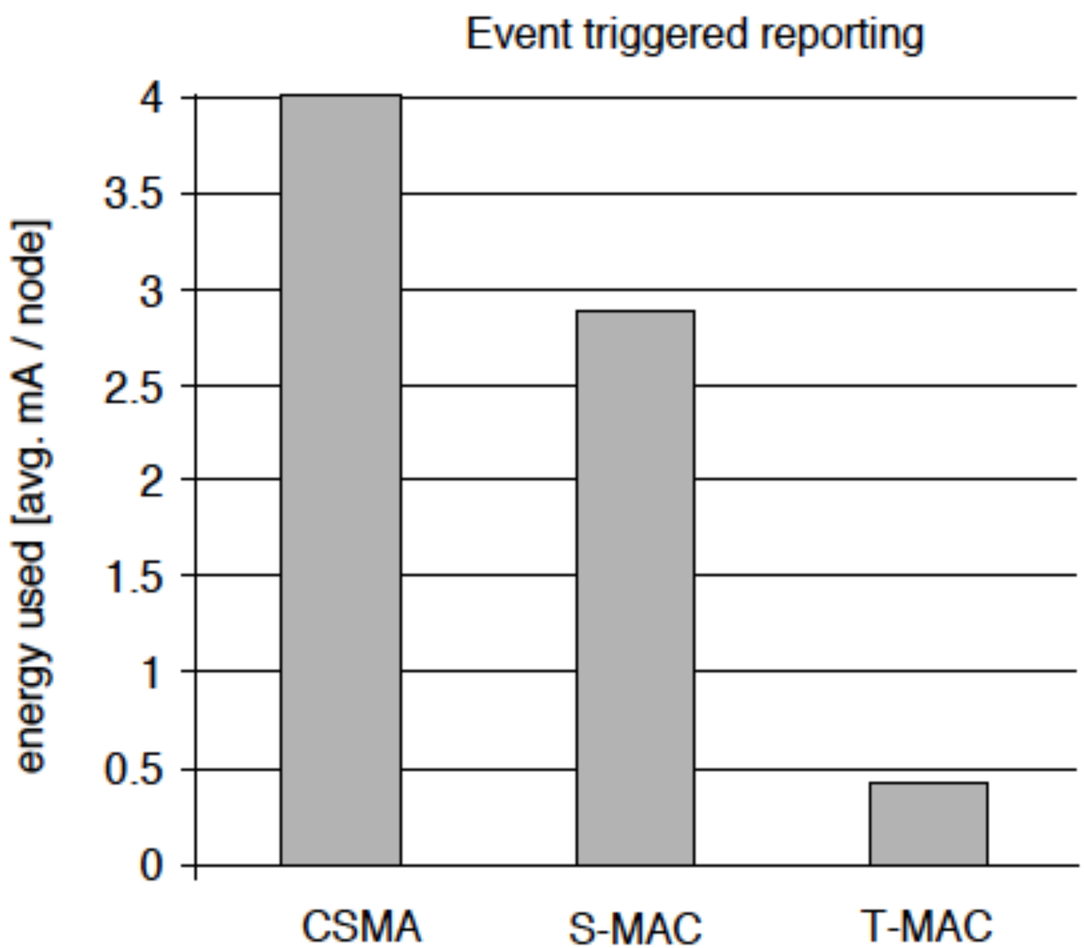


Figure 6: Taking priority upon receiving RTS.

Full buffer priority: upon receiving an RTS a node which has almost the buffer full instead of answering with a CTS sends immediately an RTS

T-MAC performance



BMAC (Berkeley Media Access Control)

- Polastre, Hill, Culler "Versatile Low Power Media Access for Wireless Sensor Networks" , ACM SenSys 2004

https://people.eecs.berkeley.edu/~culler/papers/sensys04-bmac.pdf

- Asynchronous MAC

Targets

- The MAC
- Should have low Power Operation
- Should perform effective Collision Avoidance
- Simple Implementation, Small Code and RAM Size
- Efficient Channel Utilization at Low and High Data Rates
- Reconfigurable by Network Protocols
- Tolerant to Changing RF/Networking Conditions
  - links can be dynamic
- Scalable to Large Numbers of Nodes

B-MAC

- For effective collision avoidance, a MAC protocol must be able to accurately determine if the channel is clear—Clear Channel Assessment or CCA
  - BMAC proposes a way to estimate the channel noise and to determine whether the channel is free (taking some samples and checking whether any of the sample is below the average noise level)
    - ✓ the proposed solution for channel assessment has been validated with experimental data
    - ✓ queue of RSSI samples (10), median of the samples used to compute an exponentially weighted moving average with decay factor alpha (0.06) →noise floor estimation
    - ✓ CCA samples→if no outlier out of 5 samples (outlier= below noise level) then busy; otherwise free

B-MAC

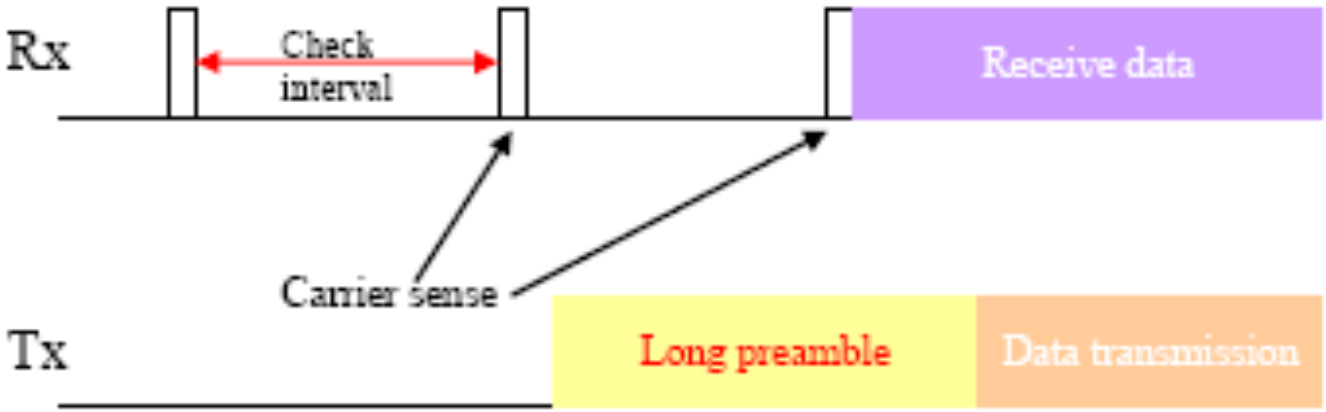
RECEIVER SIDE

- B-MAC duty cycles the radio through periodic channel sampling, called Low Power Listening (LPL)
  - Each time the node wakes up, it turns on the radio and checks for **activity**. If activity is detected, the node powers up and stays awake for the time required to receive the incoming packet. After reception (or after a timeout expiration), the node returns to sleep.

TRANSMITTER SIDE

- The sender transmits a preamble, then the data
  - To reliably receive data, the preamble length is matched to the interval that the channel is checked for activity

Shifts most burden to the sender



<u>Challenge</u>

Check interval has to be short to ensure reasonable size preambles

XMAC

Buettner,Yee,Anderson, Han “X-MAC: A short preamble MAC protocol for duty cycled wireless sensor networks”, ACM SenSys 2006

https://www.cs.cmu.edu/~andersoe/papers/xmac-sensys.pdf

Starting point for XMAC

- A key advantage of asynchronous low power listening protocols such as BMAC is that sender and receiver can be completely decoupled in their duty cycles
  - no need for synchronization
- BMAC long preamble in low power listening however leads to performance degradation
  - the receiver has to wait for the full period until the preamble is finished before the data/ack exchange can begin, even if the receiver has woken up at the start of the preamble
    - ✓ increase in latency and energy consumption
  - overhearing problem
    - ✓ **receivers who are not in the target of the sender also wake up during the long premable and have to stay on until the end of it to discover they are not the intended destination**
      - Increase in energy consumption!
  - latency degradation
    - ✓ per hop latency lower bounded by preamble length

XMAC

- Ideas
  - embed address info of the intended destination in the preamble
    - ✓ to avoid overhearing
  - use a *strobed preamble* : the preamble is a series of short preambles. Pauses between the short preambles allow the destination to send a fast ACK when up
    - ✓ reception of an early ACK makes the sender stop sending short preambles
      - the preamble is automatically set to the right size

This approach also solves a practical problem ← packet radios not always able to send long preambles

XMAC

- Idea:
  - en … preamble
    - ✓
  - us … ort pre … he des
    - ✓ … short

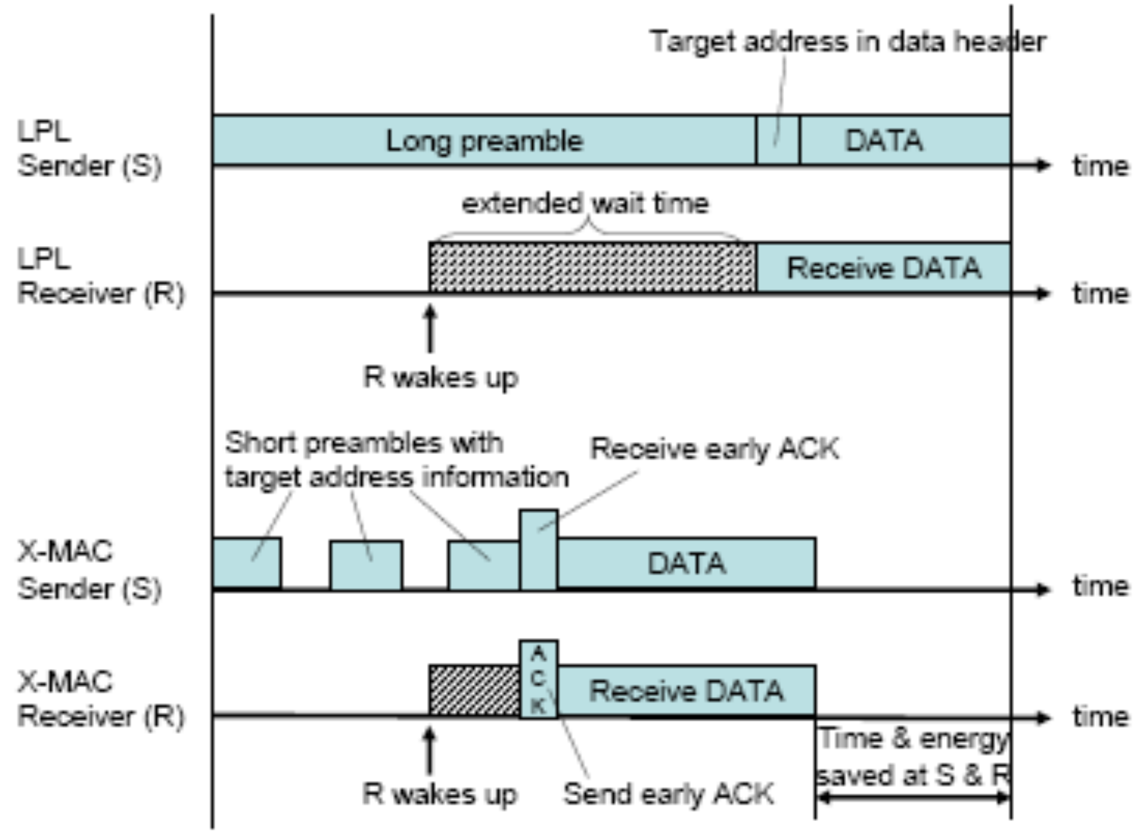


Figure 1. Comparison of the timelines between LPL's extended preamble and X-MAC's short preamble approach.

X-MAC Perf. Evaluation

- star topology, 9 sending nodes, each transmitting on average one packet per second, 500ms preamble

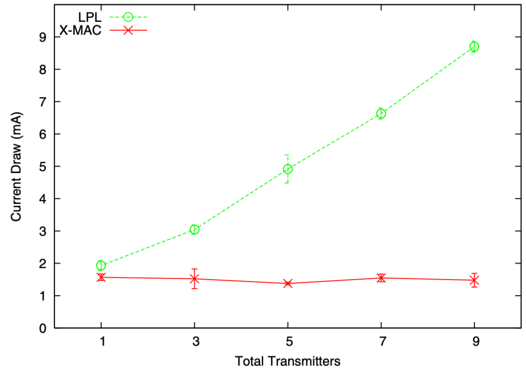
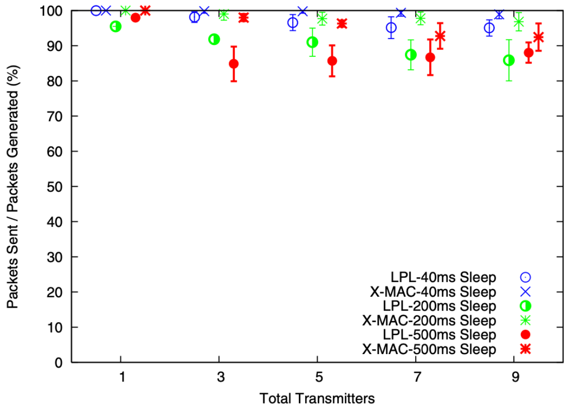
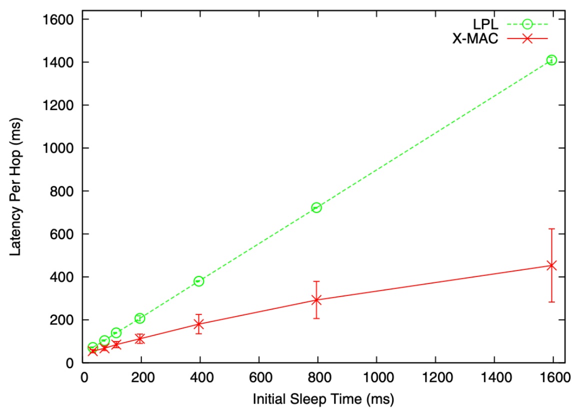


Figure 8. Power consumption per node versus density.





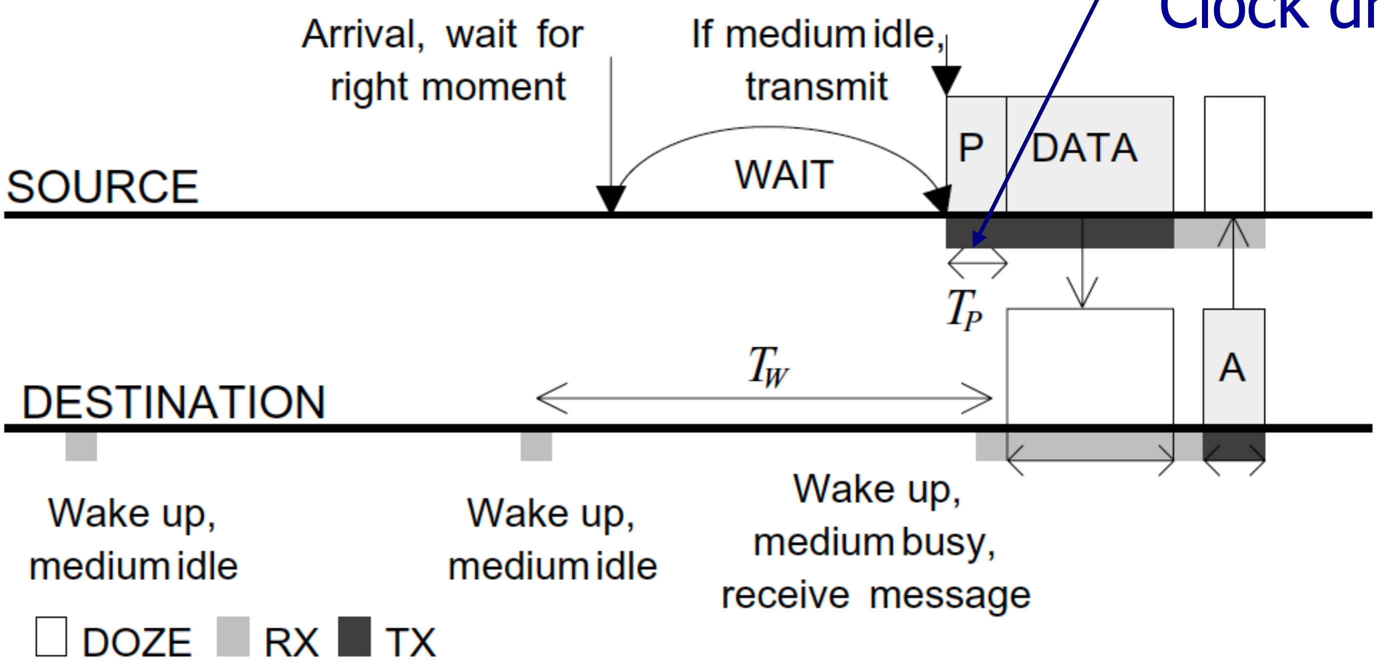
WiseMAC

- Amre El-Hoiydi and Jean-Dominique Decotignie "WiseMAC: An Ultra Low Power MAC Protocol for Multi-hop Wireless Sensor Networks", in proceedings of IEEE ISCC 2004

- Asynchronous MAC

WiseMAC

Accounts for
Clock drifts



Let θ be the frequency tolerance of the time-base quartz

Clock Drift

- Crystal Clock accuracy is defined in terms of ppm (ppm= parts per million).
- What is the error you will encounter when using a clock of a specific type with a specific accuracy?
- Realistic example: RTC clock on an IoT device with a drift around 10ppm.
- 10ppm=10/10e6=10-5
- 86400 seconds in a day
- Total error of 86400*10-5=0,8s per day
- This translates in a max drift of about 300 seconds for 6 months of operation (each clock +/- θ according to the ppm error).

IoT Standardization

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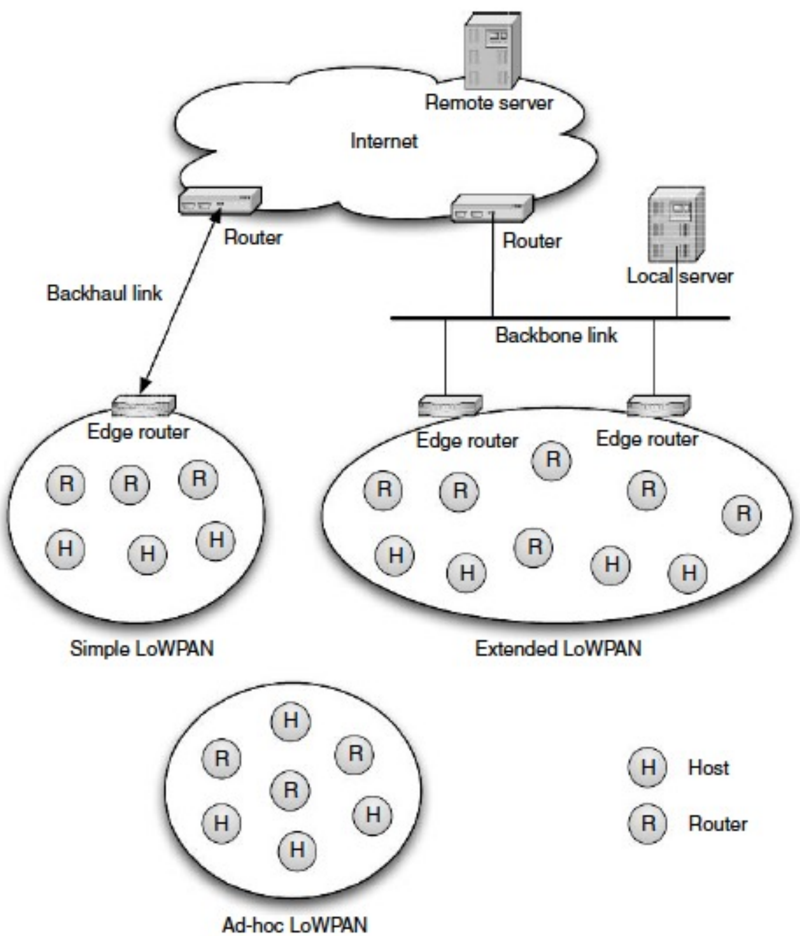
IoT Standardization

- ✓ 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)

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

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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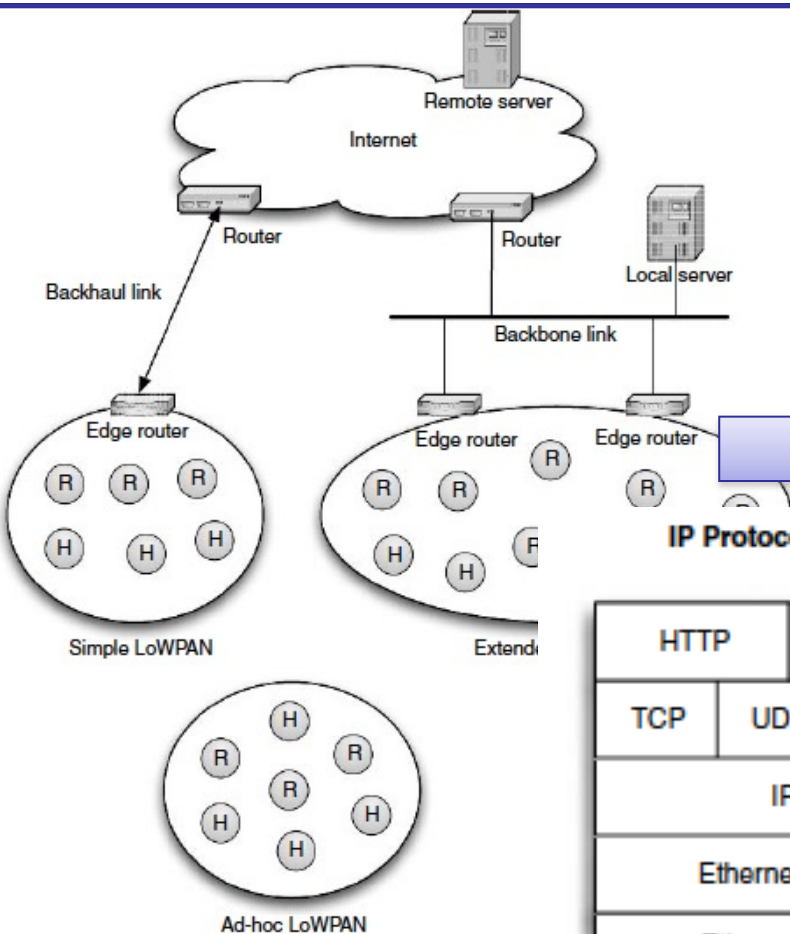
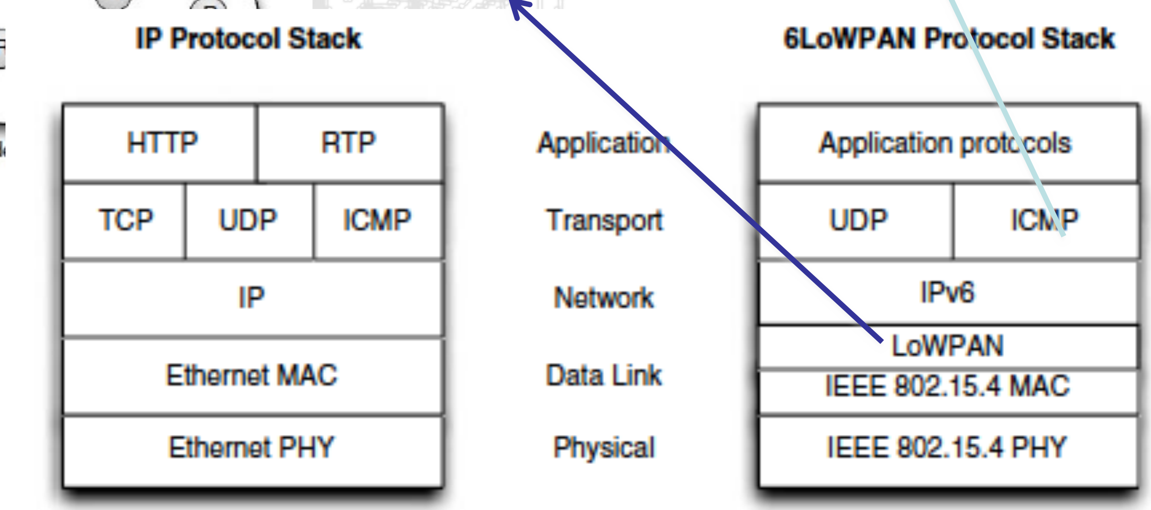


Control messages

Neighbor discovery

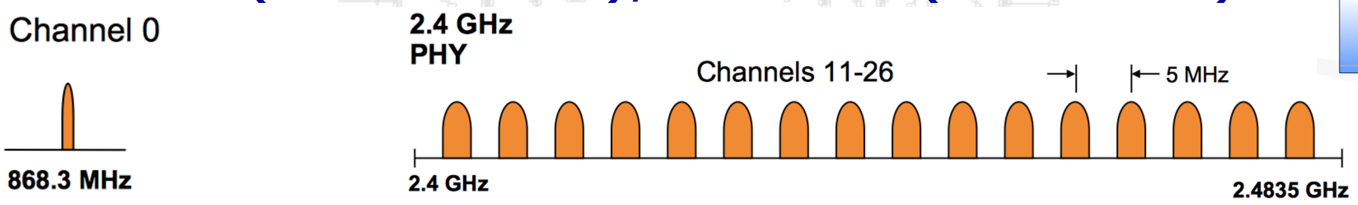
Adaptation layer



IEEE 802.15.4

	Channel	Center Frequency (MHz)	Availability
868 MHz Band	0	868.3	Europe
915 MHz Band	1	906	Americas
	2	908	
	3	910	
	4	912	
	5	914	
	6	916	
	7	918	
	8	920	
	9	922	
	10	924	
2.4 GHz Band	11	2405	World Wide
	12	2410	
	13	2415	
	14	2420	
	15	2425	
	16	2430	
	17	2435	
	18	2440	
	19	2445	
	20	2450	
	21	2455	
	22	2460	
	23	2465	
	24	2470	
	25	2475	
	26	2480	

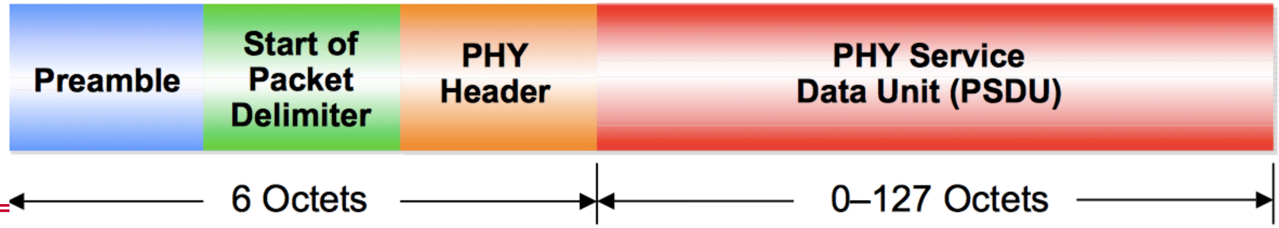
- ISM 2.4Ghz (16 channels), 868MHz (1 channel)



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

PHY Packet Fields

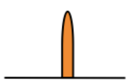
- Preamble (32 bits) – synchronization
- Start of Packet Delimiter (8 bits)
- PHY Header (8 bits) – PSDU length
- PSDU (0 to 1016 bits) – Data field



IEEE 802.15.4

- ISM 2.4G…

Channel 0



868.3 MHz

- 20Kbps (8…
- Packet str…

PH…

- P…
- S…
- P…
- P…

Pre…

	Channel	Center Frequency (MHz)	Availability
868 MHz Band	0	868.3	 Europe
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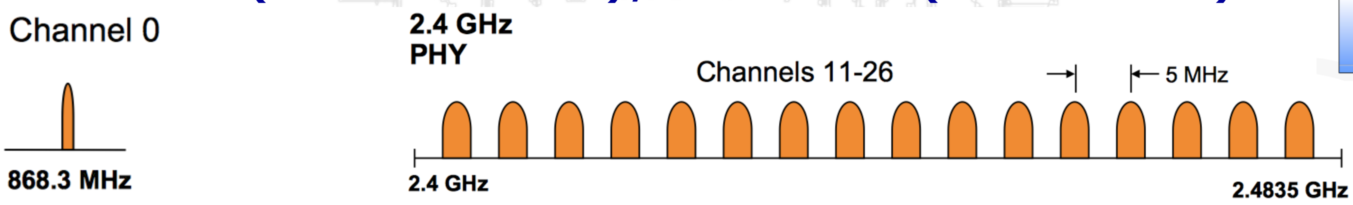

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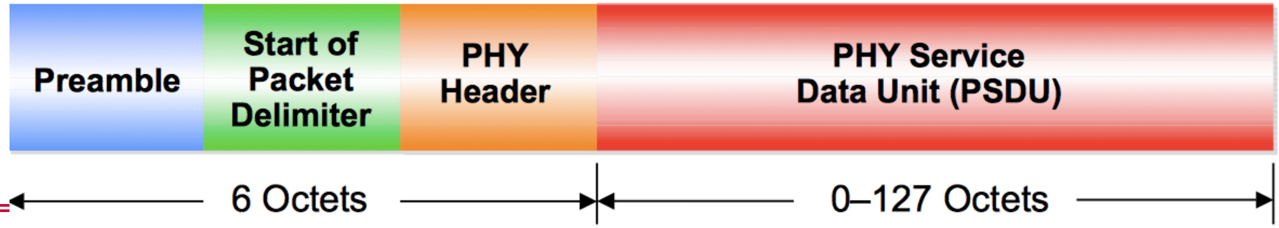
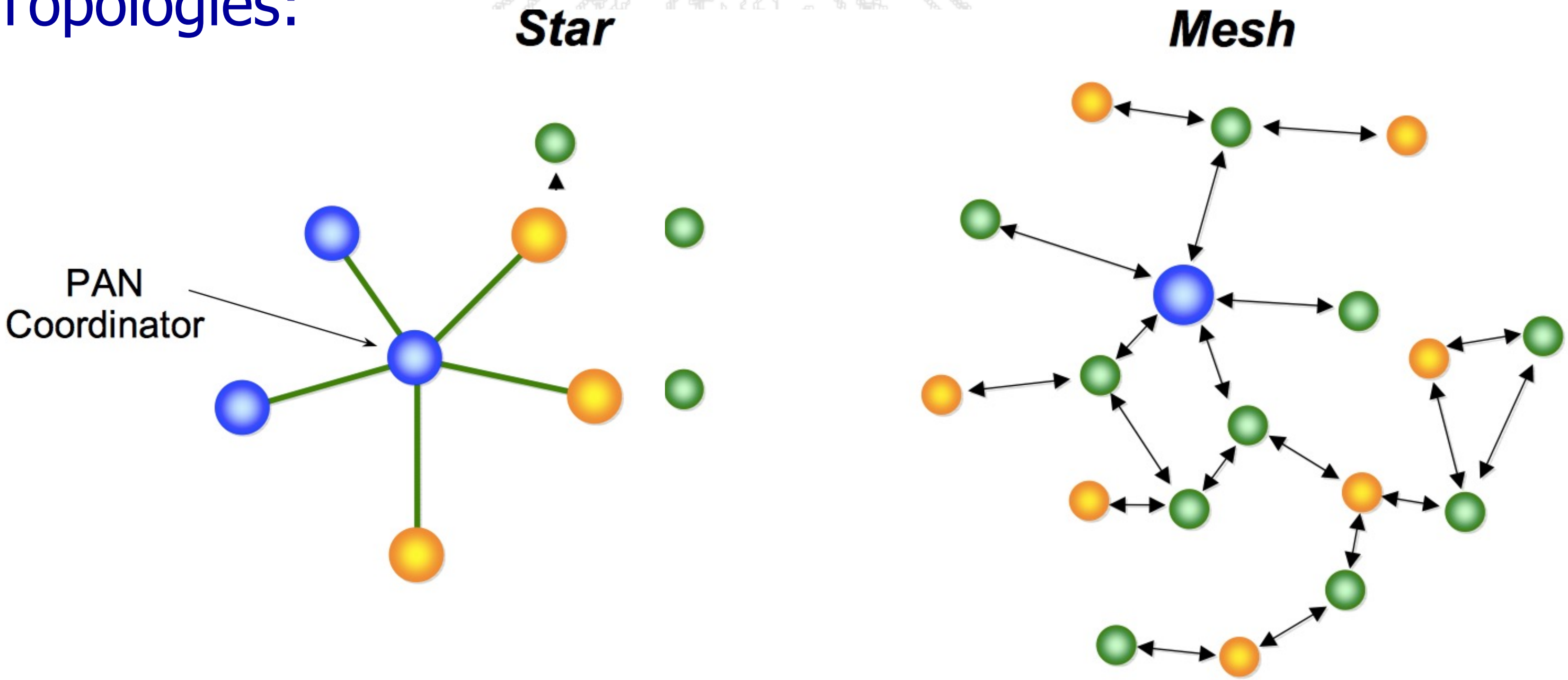
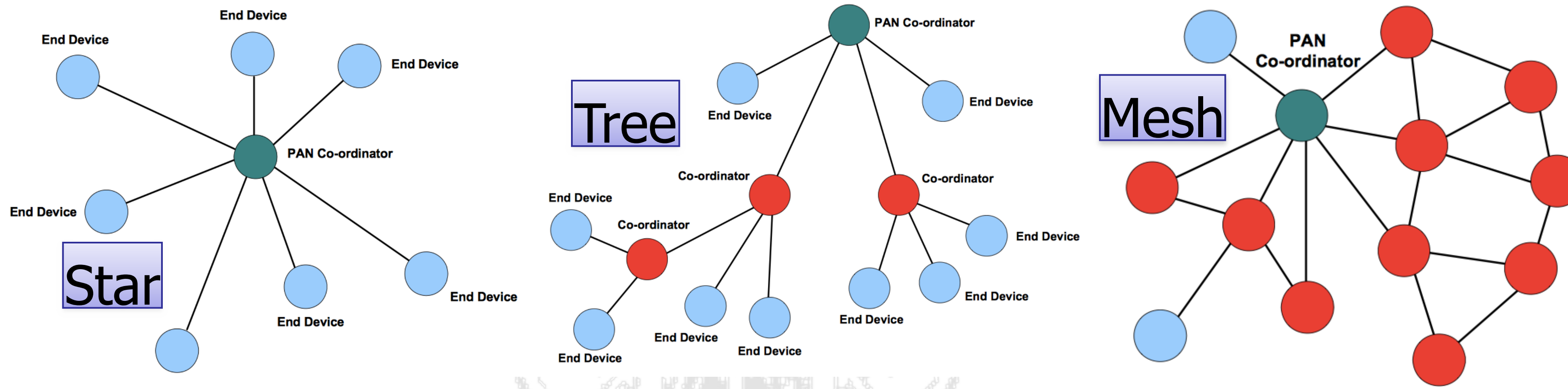


IEEE 802.15.4

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



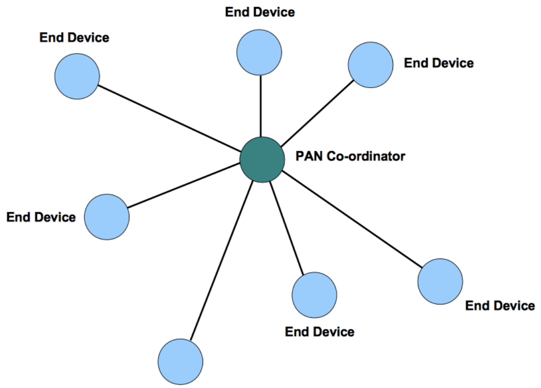
- Very low power operation
  - low power transmitter/receiver
  - nodes can duty cycle
- Topologies:



  - 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



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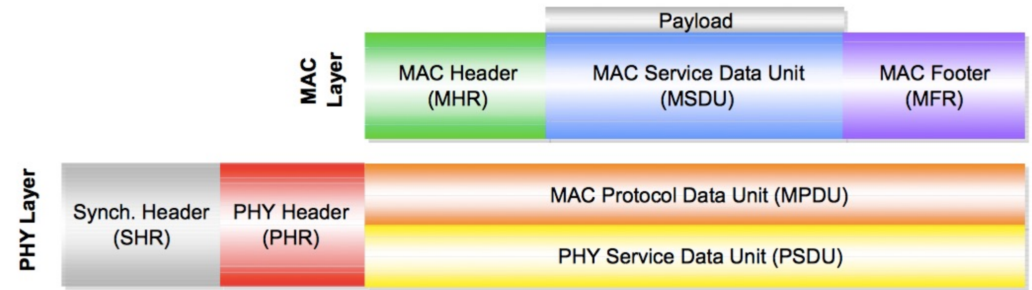
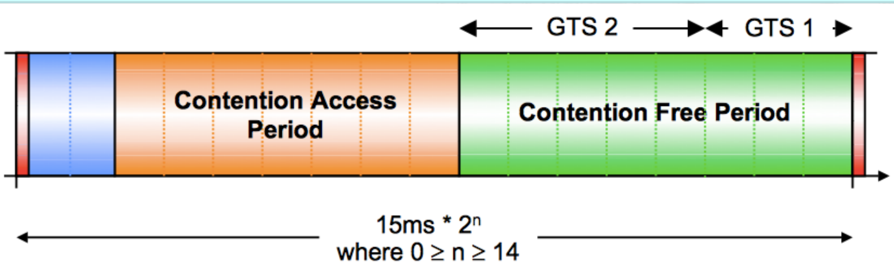
IEEE 802.15.4 MAC



- ✓ 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

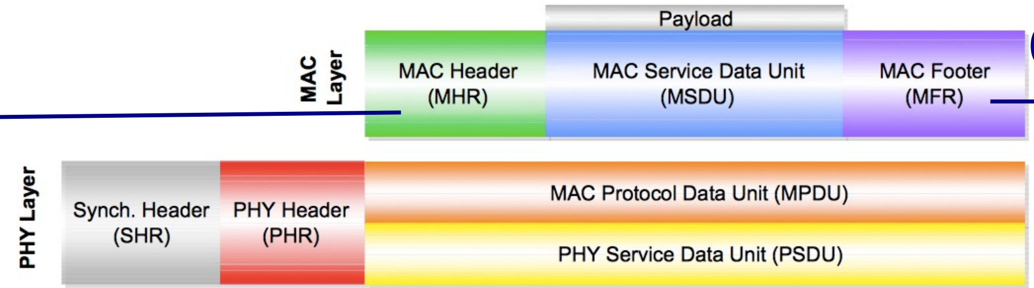
Beacon Extension Period—Space reserved for beacon growth due tc pending node messages

Contention Period—Access by any node using CSMA-CA

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

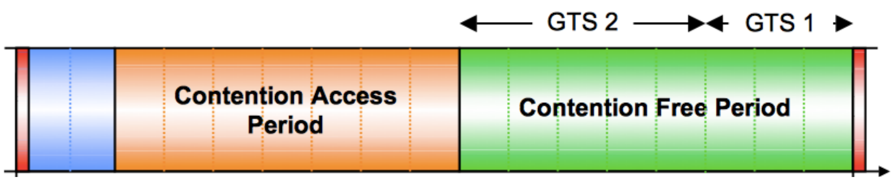
IEEE 802.15.4 MAC

Address, SN



CRC

- ✓ 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.

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

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.

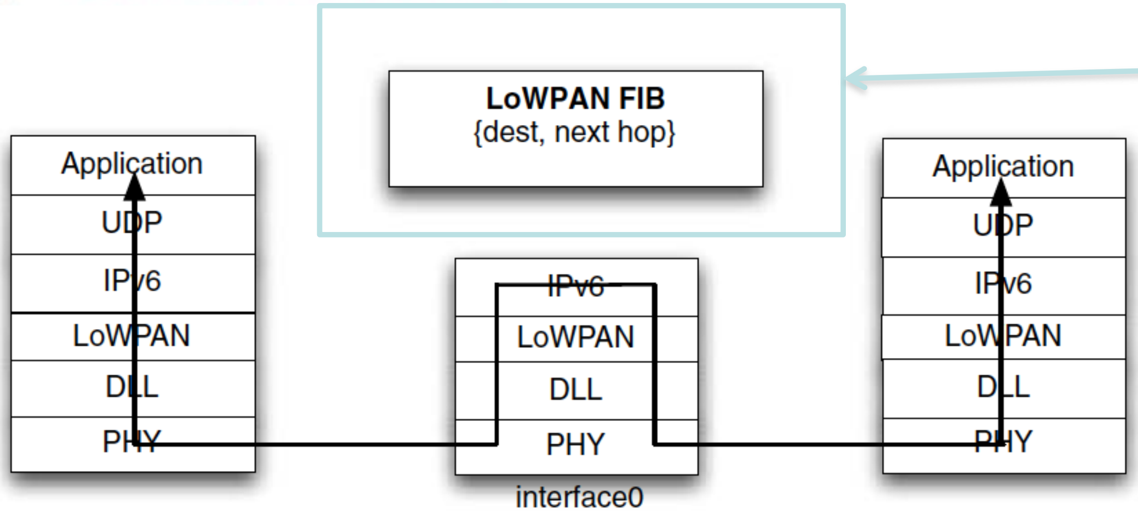
Adaptation layer: 6LoWPAN

- 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.

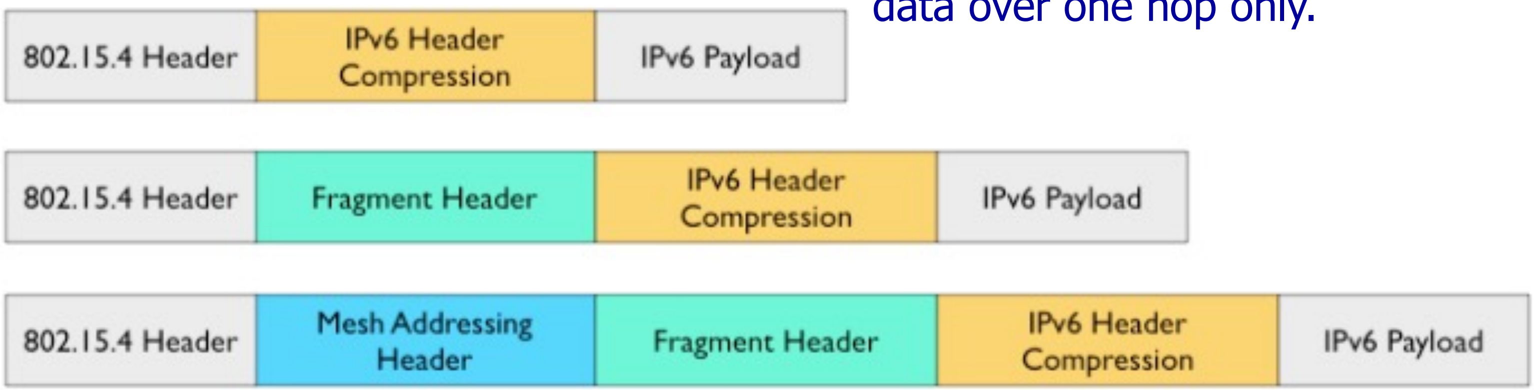


Figure 2. Typical 6LoWPAN Header Stacks.

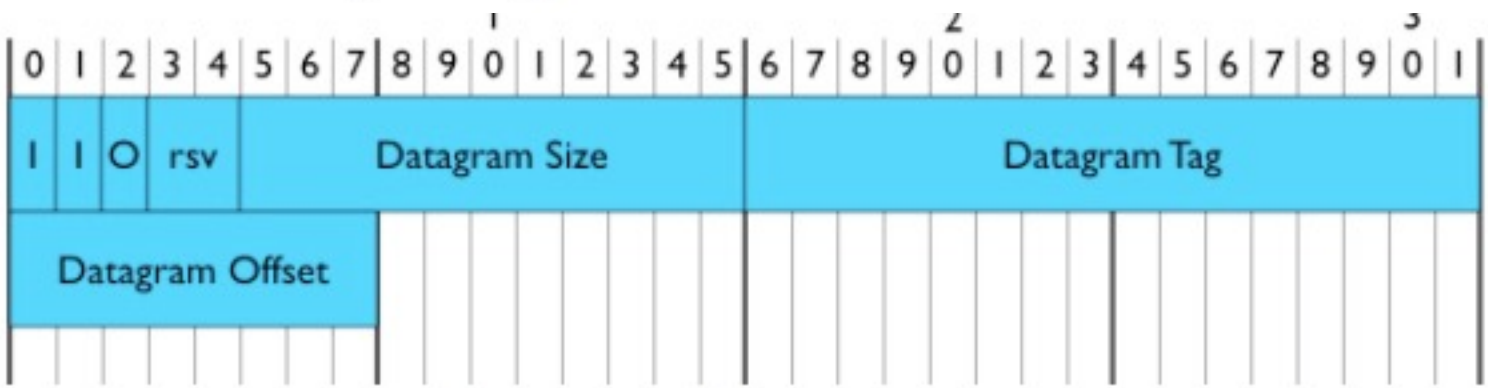


Figure 3. 6LoWPAN Fragment Header.

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

6LowPAN

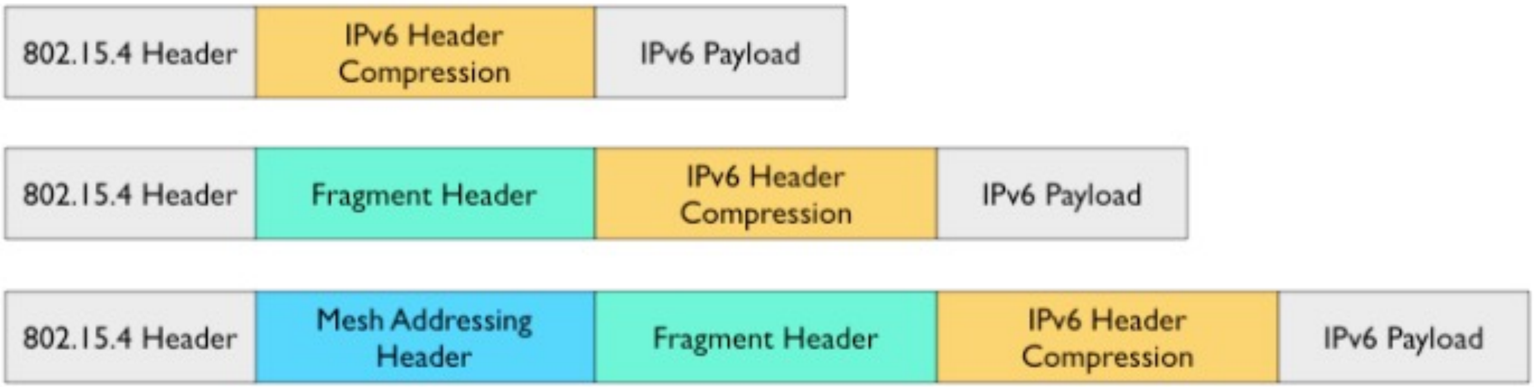
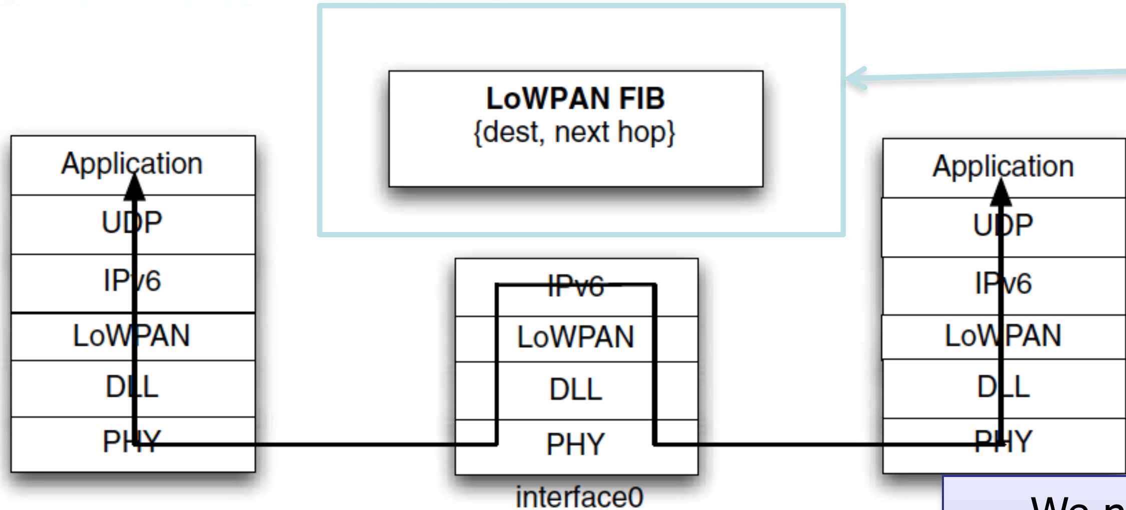


Figure 2. Typical 6LoWPAN Header Stacks.

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)

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.

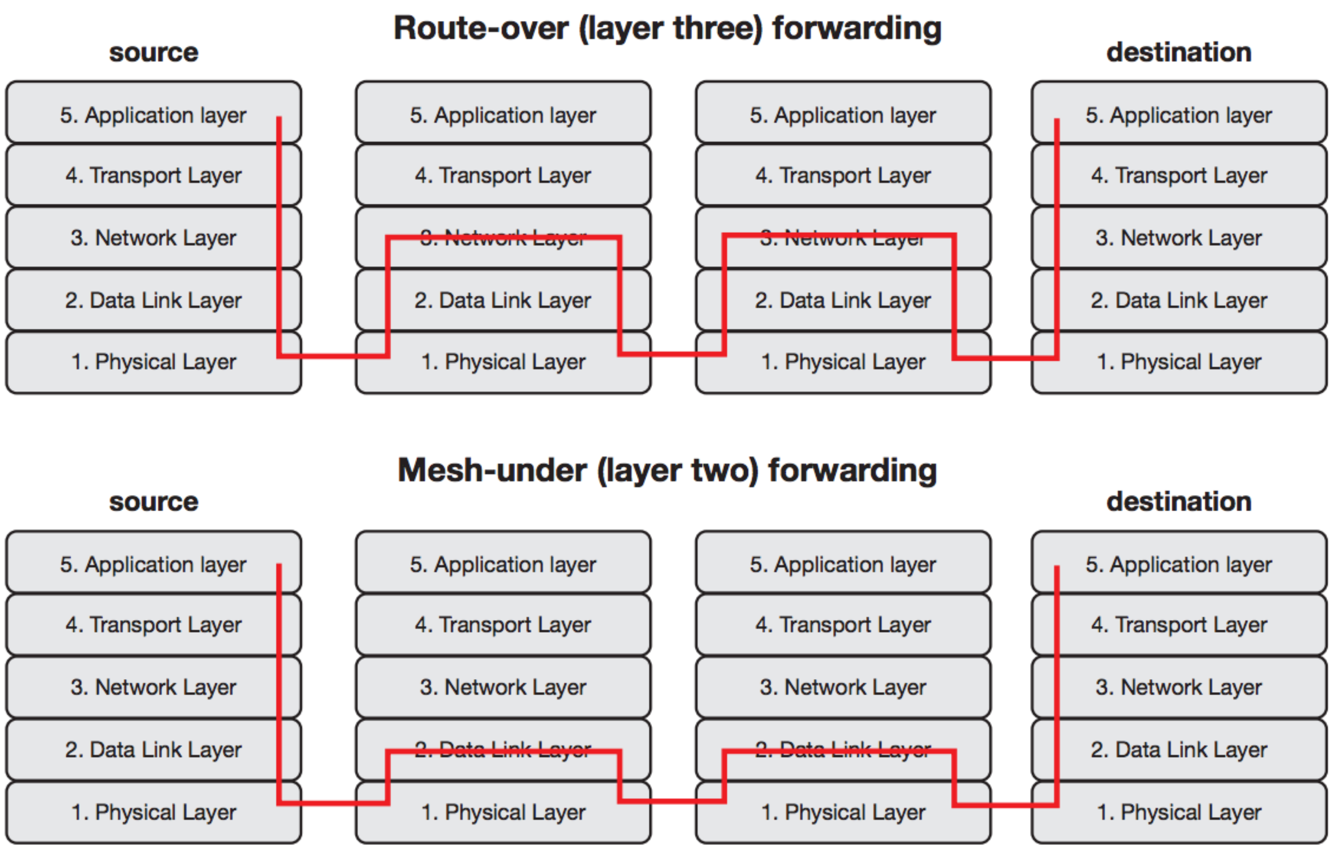


Figure 5. Mesh-under and route-over packet forwarding

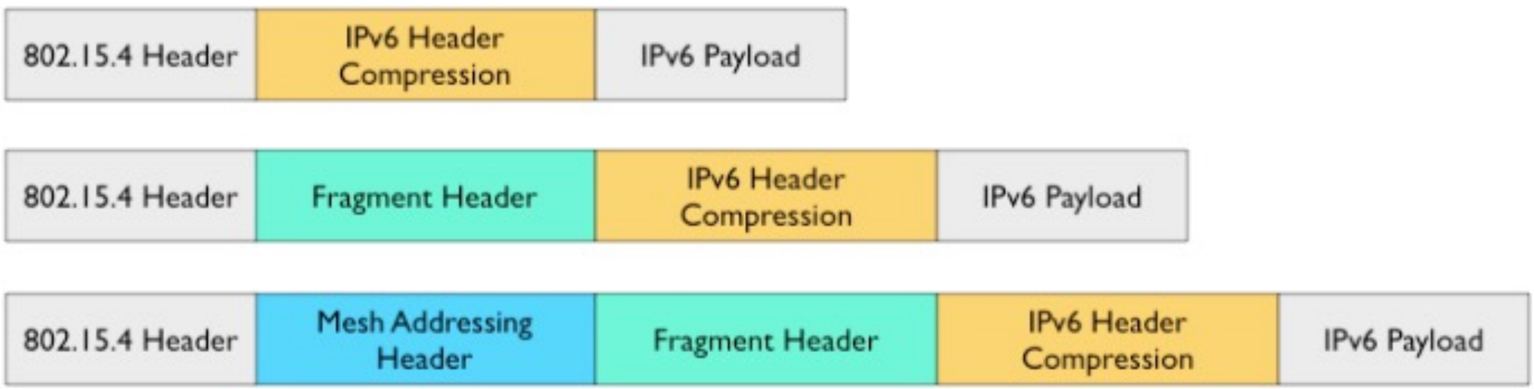


Figure 2. Typical 6LoWPAN Header Stacks.

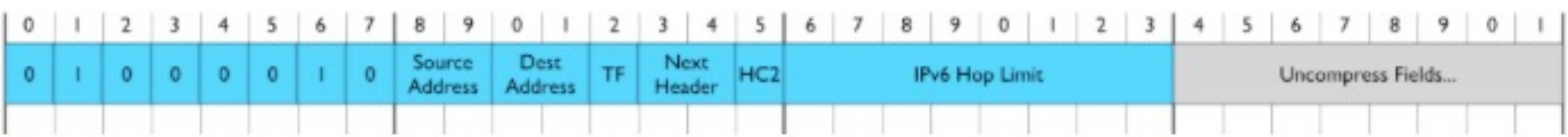
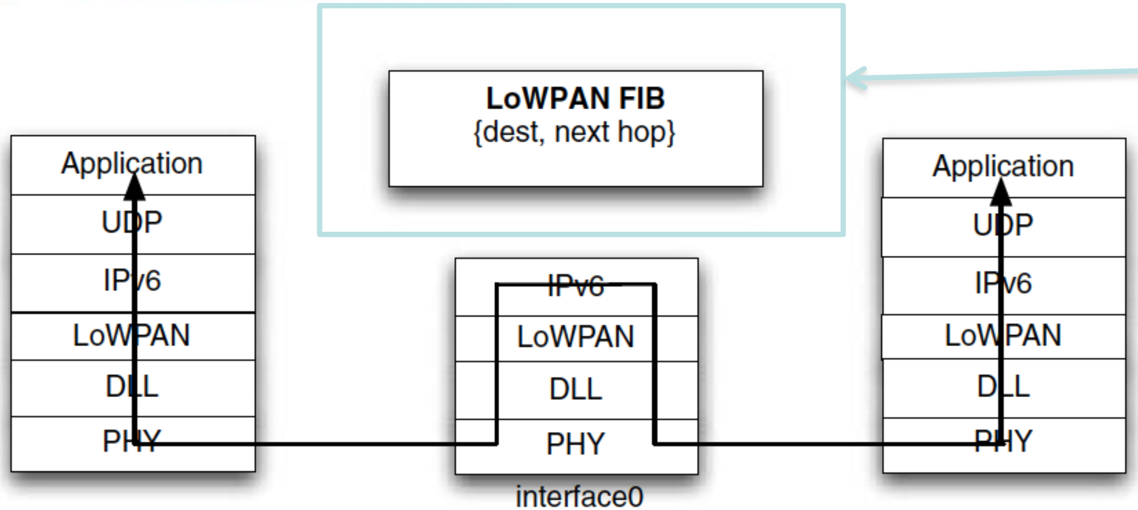


Figure 5. 6LoWPAN RFC 4944 IPv6 Header Compression.

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

Used to avoid transmitting First 64 bits of the address

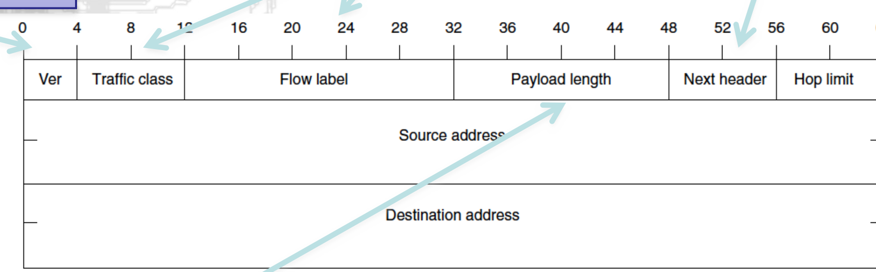
Always 6 not transmitted in HC1

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

```
                     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_/
```



Can be inferred by other Headers--Not transmitted

IPv6 packet header

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_/
```

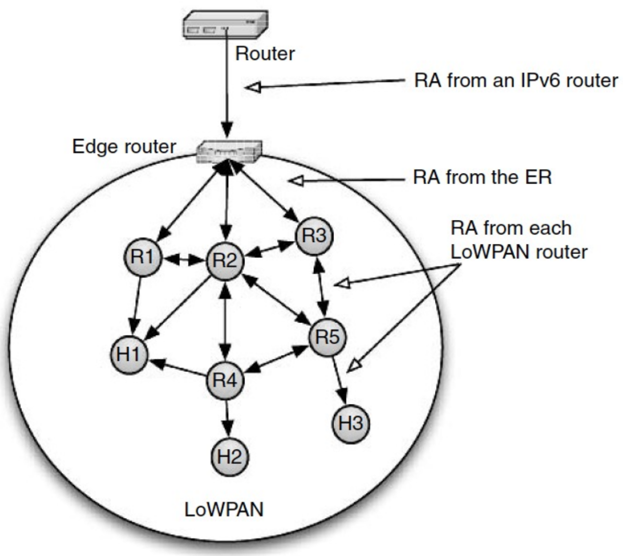
Source/destination port field compression

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 (they select the router to affiliate to based on ER metric; Node registration/confirmation)
- Procedure to assign local addresses, identify and solve duplicate addresses.

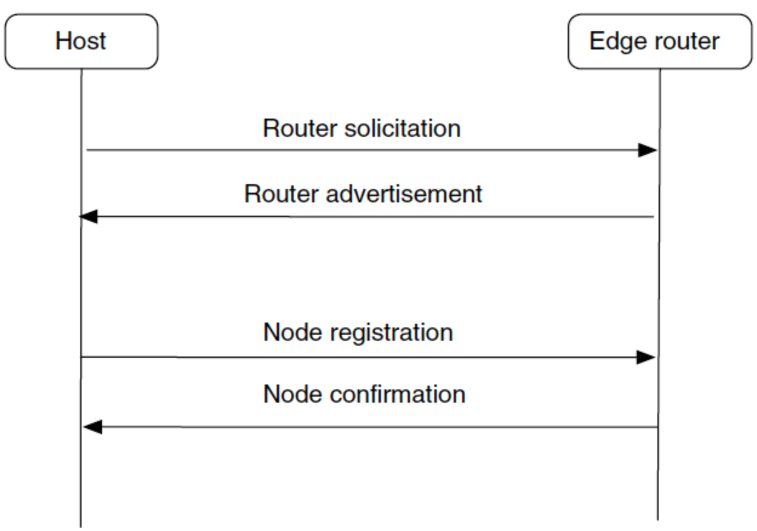



```
 0                   1
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0|1|LOWPAN_BC0 |Sequence Number|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/
```

Broadcast packet

Bootstrapping an IoT network

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

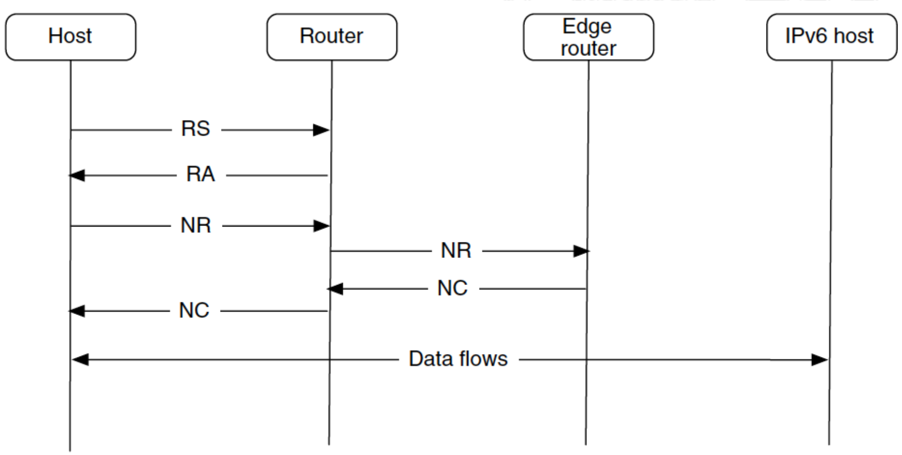



```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| Type (NR)/(NC)|     Code      |          Checksum             |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|      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       ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

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

Standard-like routing Protocols for WSNs

Internet of Things a.a. 2020/2021

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 (start from this second paper)

Omprakash Gnawali (Stanford University)

Rodrigo Fonseca (Brown University)

Kyle Jamieson (University College London)

David Moss (People Power Company)

Philip Levis (Stanford University)

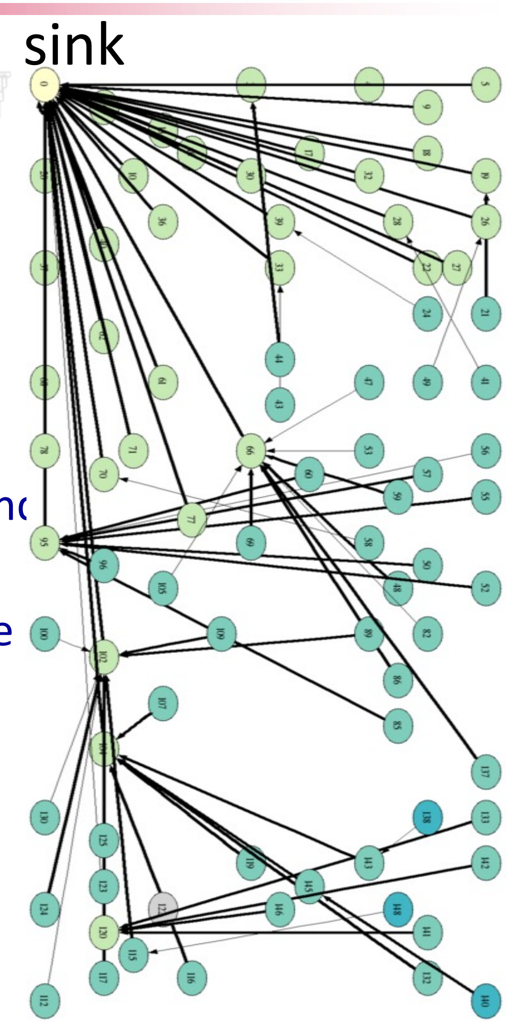
Slides partially taken from the presentation given by the authors at

ACM SenSys

November 4, 2009

Collection

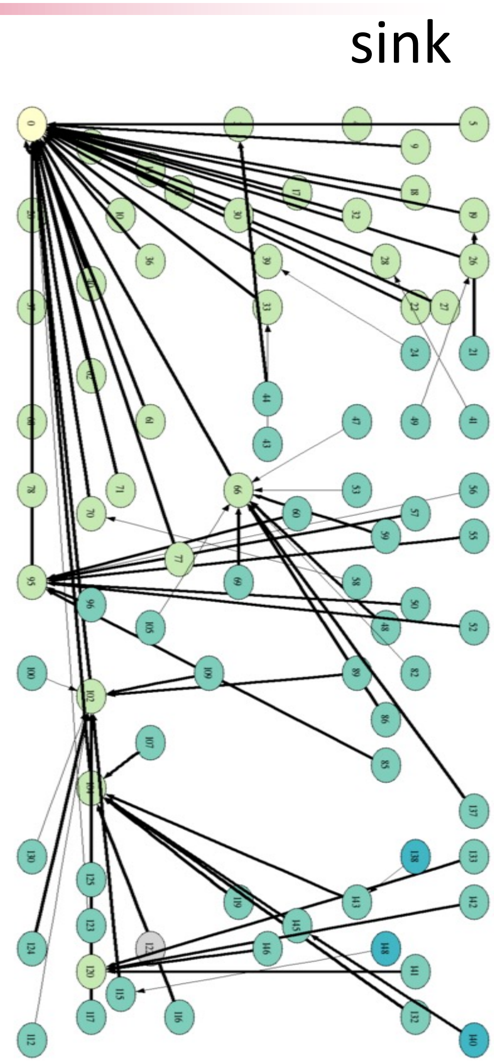
- Anycast route to the sink(s)
  - Used to collect data from the network to a small number of sinks (roots, base stations)
  - Each node selects one of its neighbors nodes as its parent
    - ✓ Parents handle packets received from the children anc further forward them towards the sink
    - ✓ when there are multiple sinks, data re 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

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



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

Parer

Pull bit

- ETX = Expected Number of Tra

Congested bit

- Comput… forma… past by beacon and data packe

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

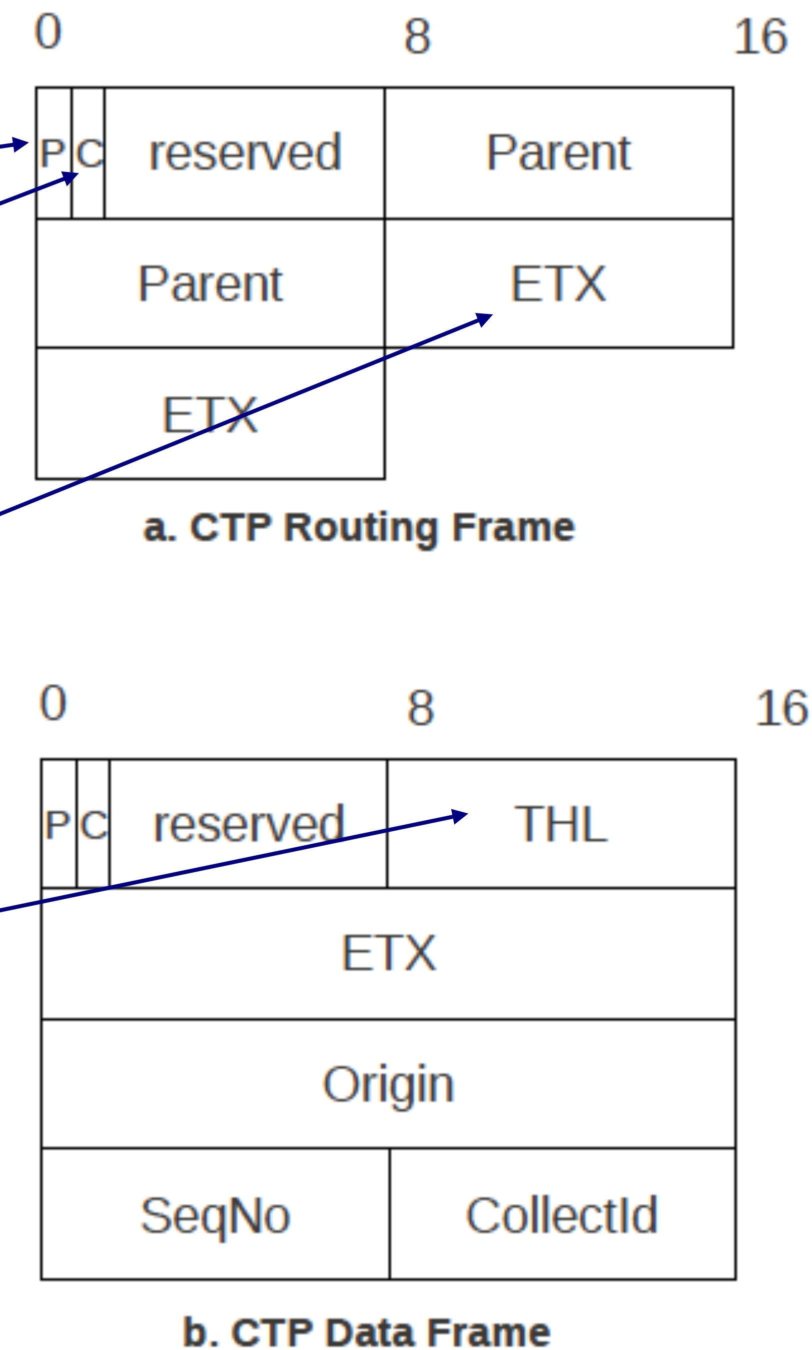
Routing cost

= (

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

Time has lived

Parent selected only amor



Common Architecture

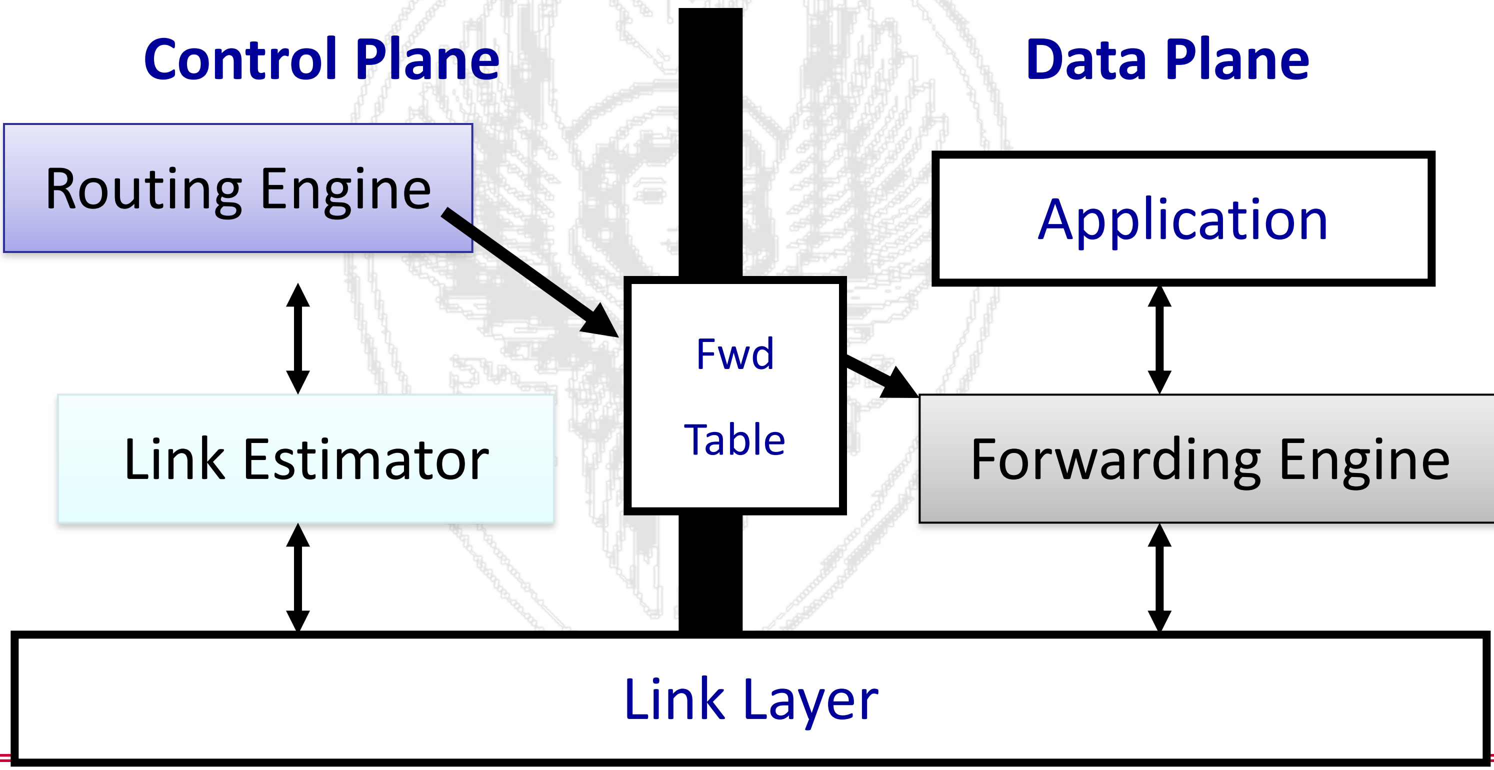
Sending and receiving beacons

for route construction and maintenance

Creating and updating the routing table

Perform forwarding

Detect and Repair Loops, filter duplicate packets



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Parer

Pull bit

- ETX = Expected Number of Tra

Congested bit

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

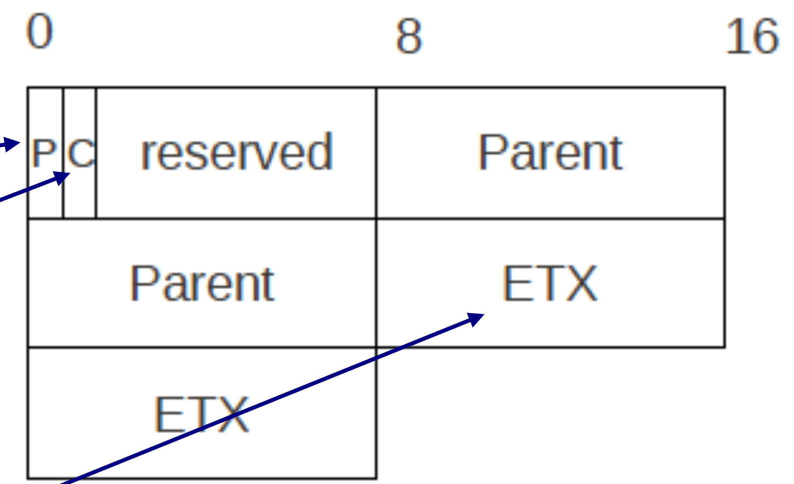
$$Q_u = \frac{n_u}{n_a}.$$

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



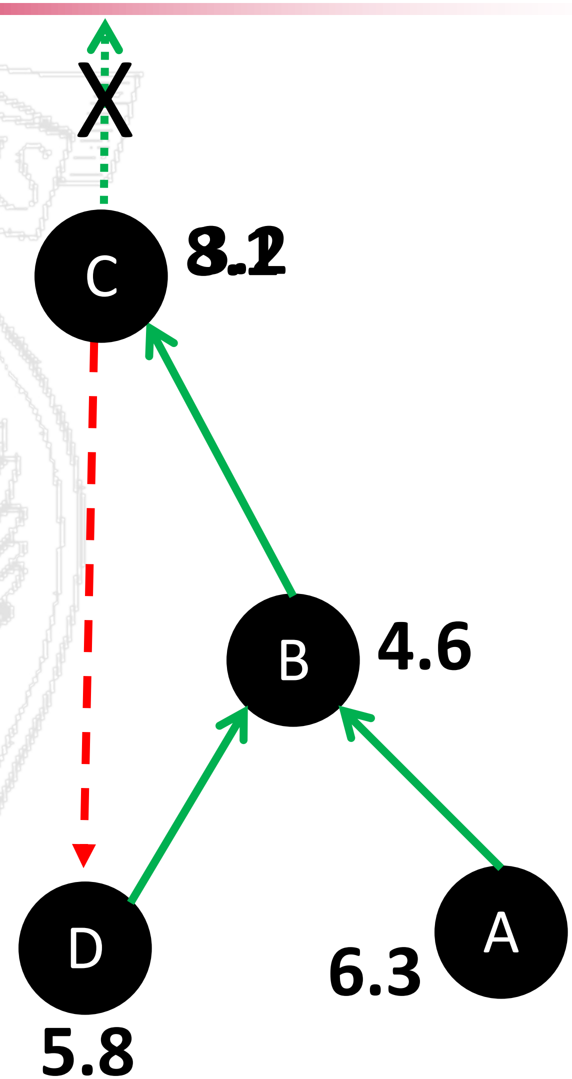
a. CTP Routing Frame

b. CTP Data Frame

Routing Loops

– Cost does not decrease

Parent selected as the neighbor with lowest cost

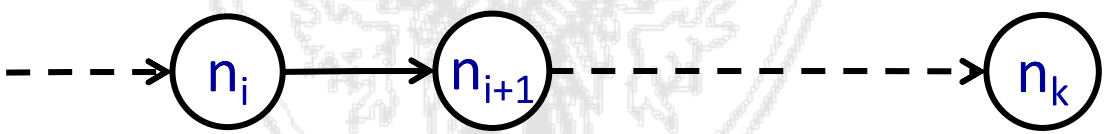


Routing Consistency

- *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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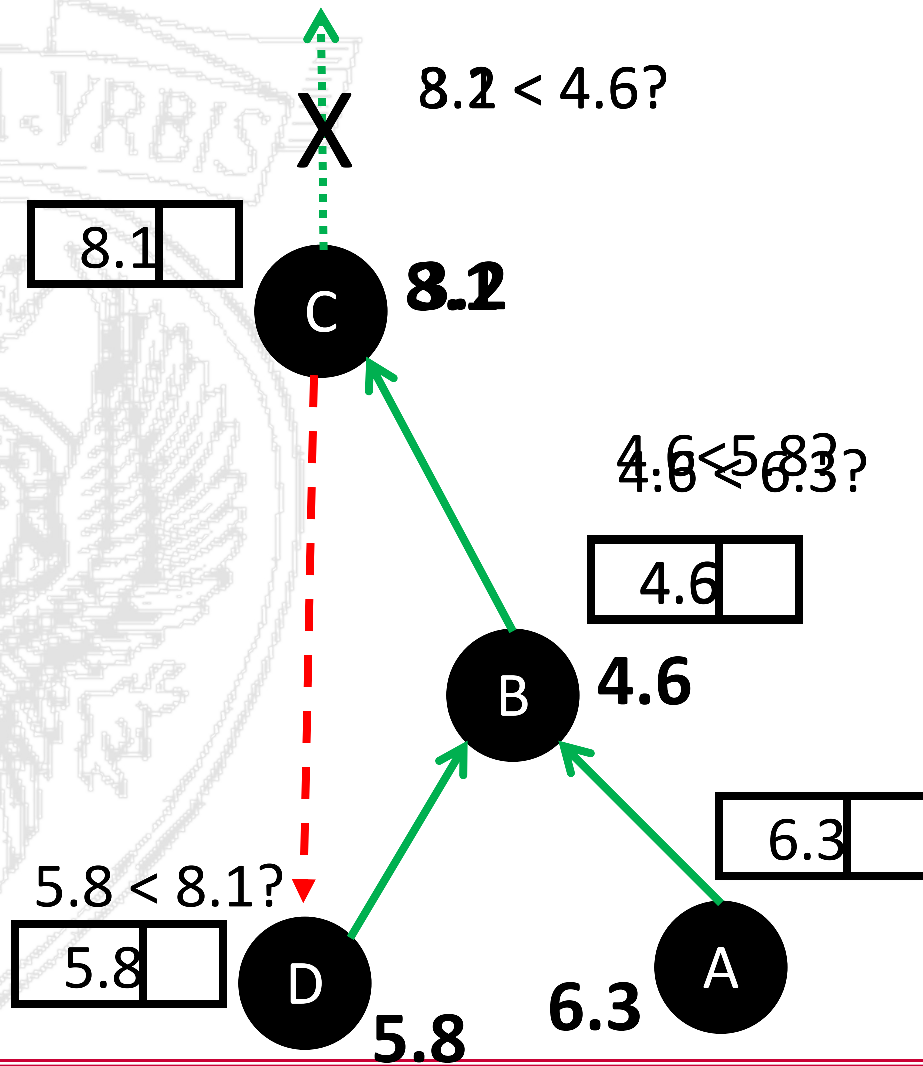
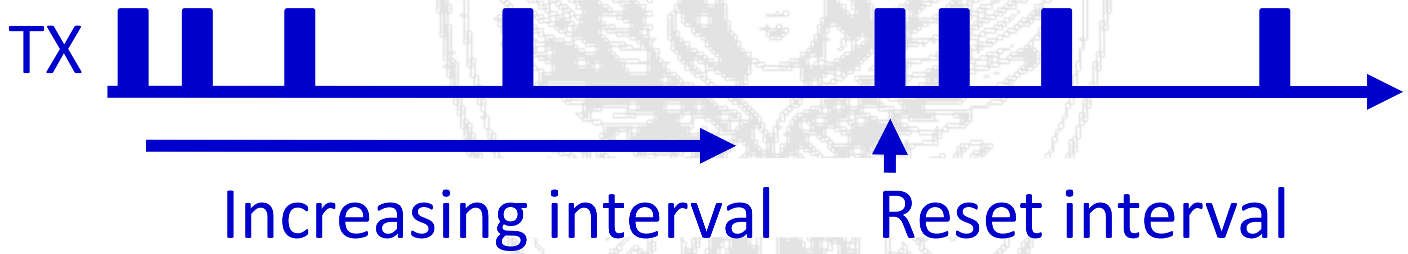
Detecting Routing Loops

- 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



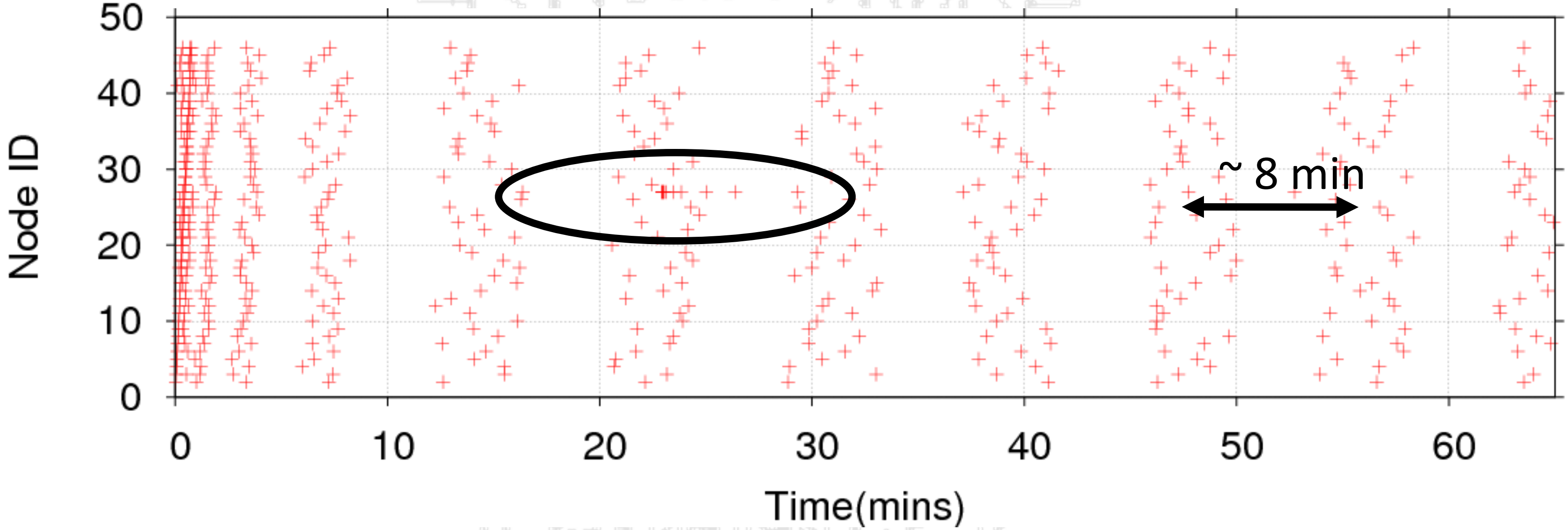
Control Traffic Timing

- 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

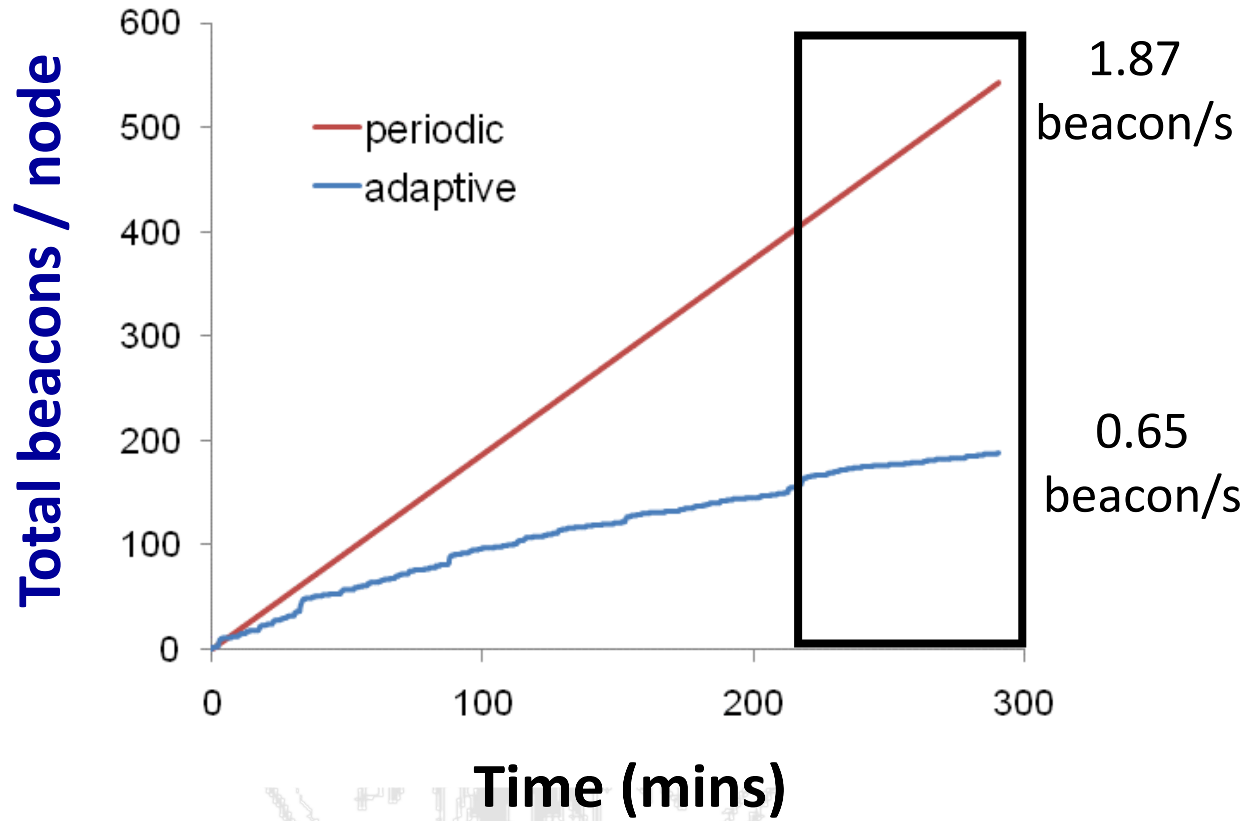
Adaptive Beacon Timing



Tutornet

Infrequent beacons in the long run

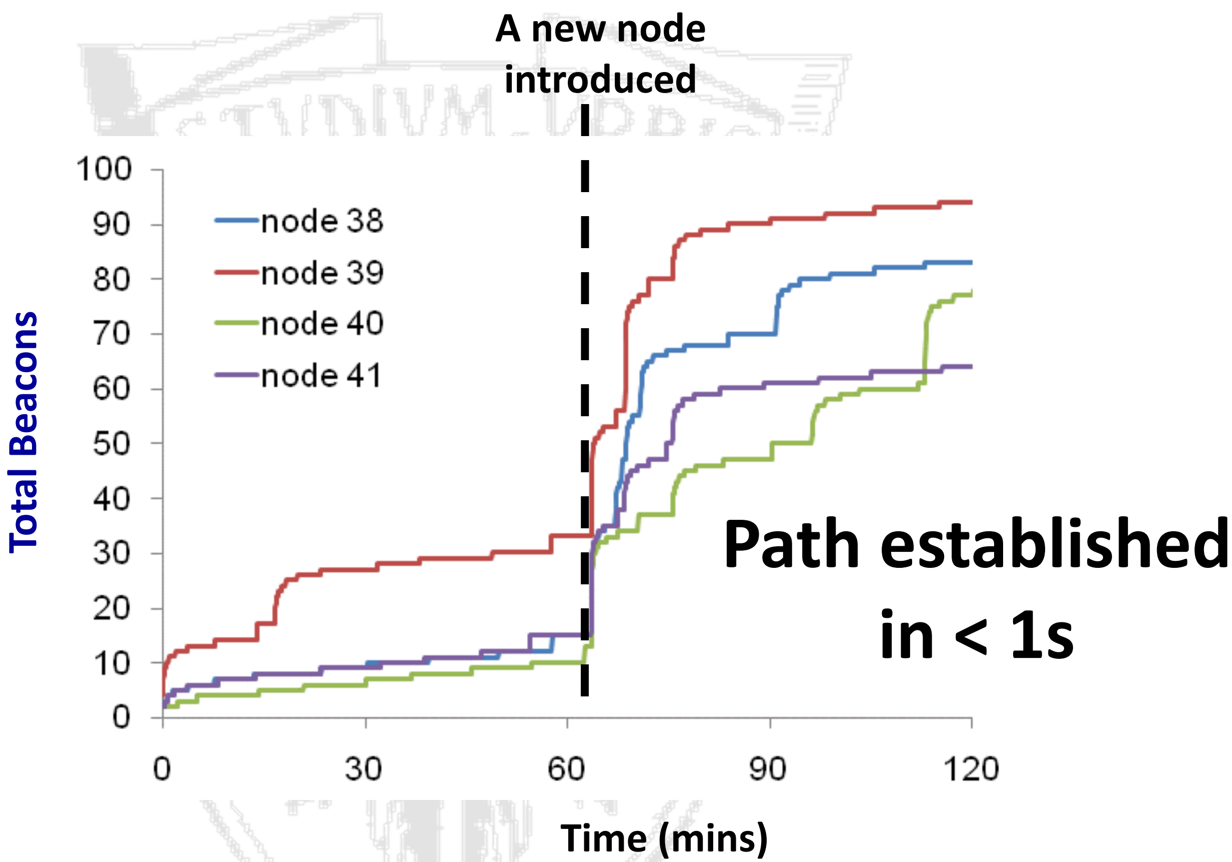
Adaptive vs Periodic Beacons



Tutornet

Less overhead compared to 30s-periodic

Node Discovery



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	$50\times25\times10$
Wymanpark	Tmote	47	80×10
Motelab	Tmote	131	$40\times20\times15$
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	$30\times13\times17$
Twist	eyesIFXv2	102	$30\times13\times17$
Vinelab	Tmote	48	60×30
Blaze	Blaze	20	30×30

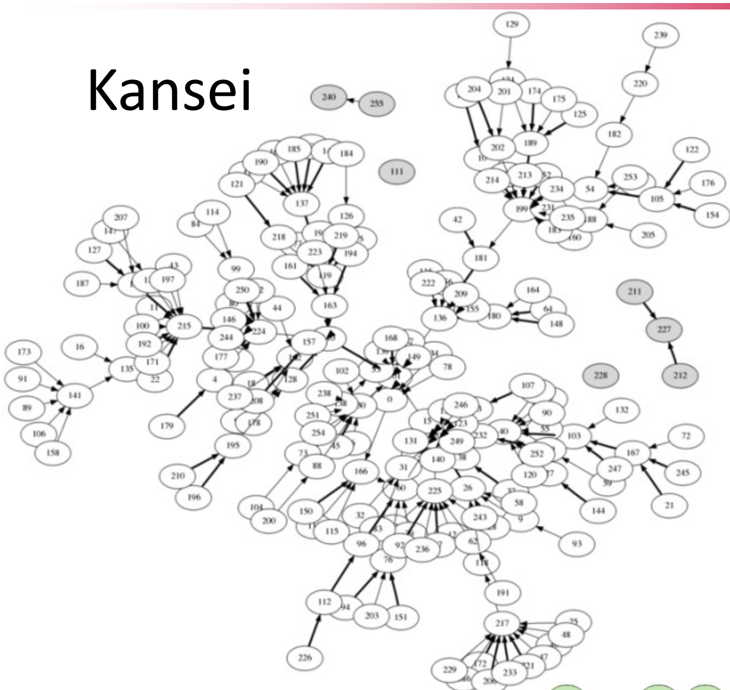
Variations in hardware, software, RF environment, and topology

Evaluation Goals

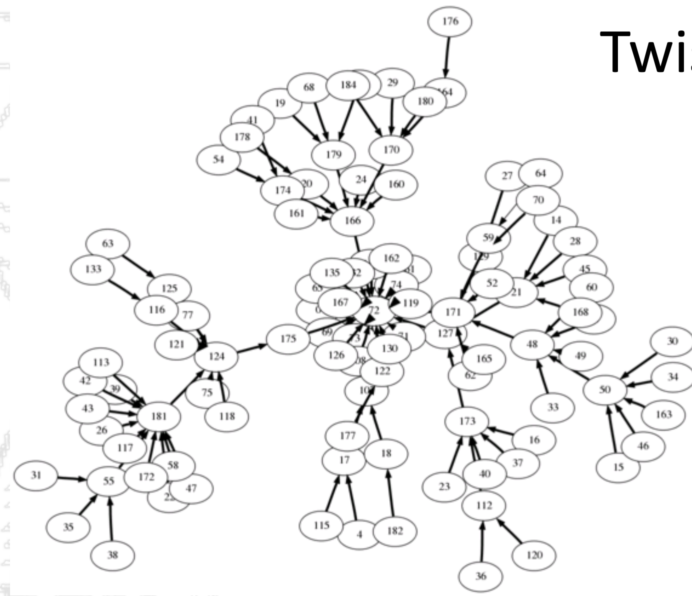
- Reliable?
  - Packets delivered to the sink
- Efficient?
  - TX required per packet delivery
- Robust?
  - Performance with disruption

CTP Noe Trees

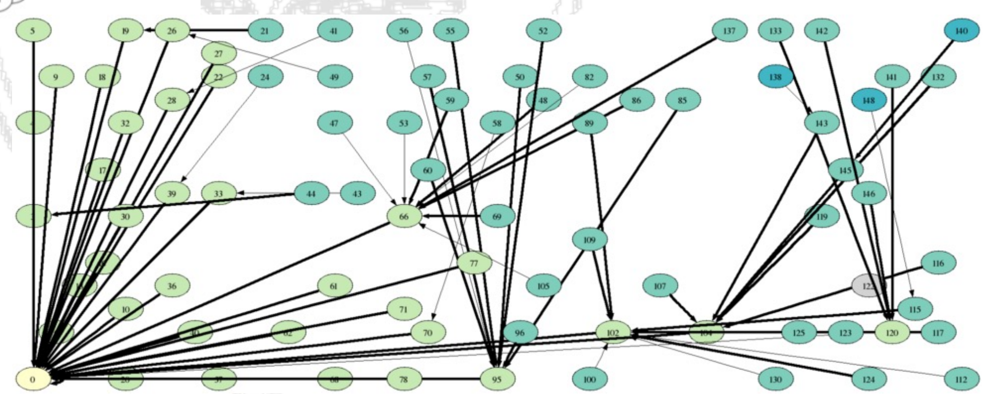
Kansei

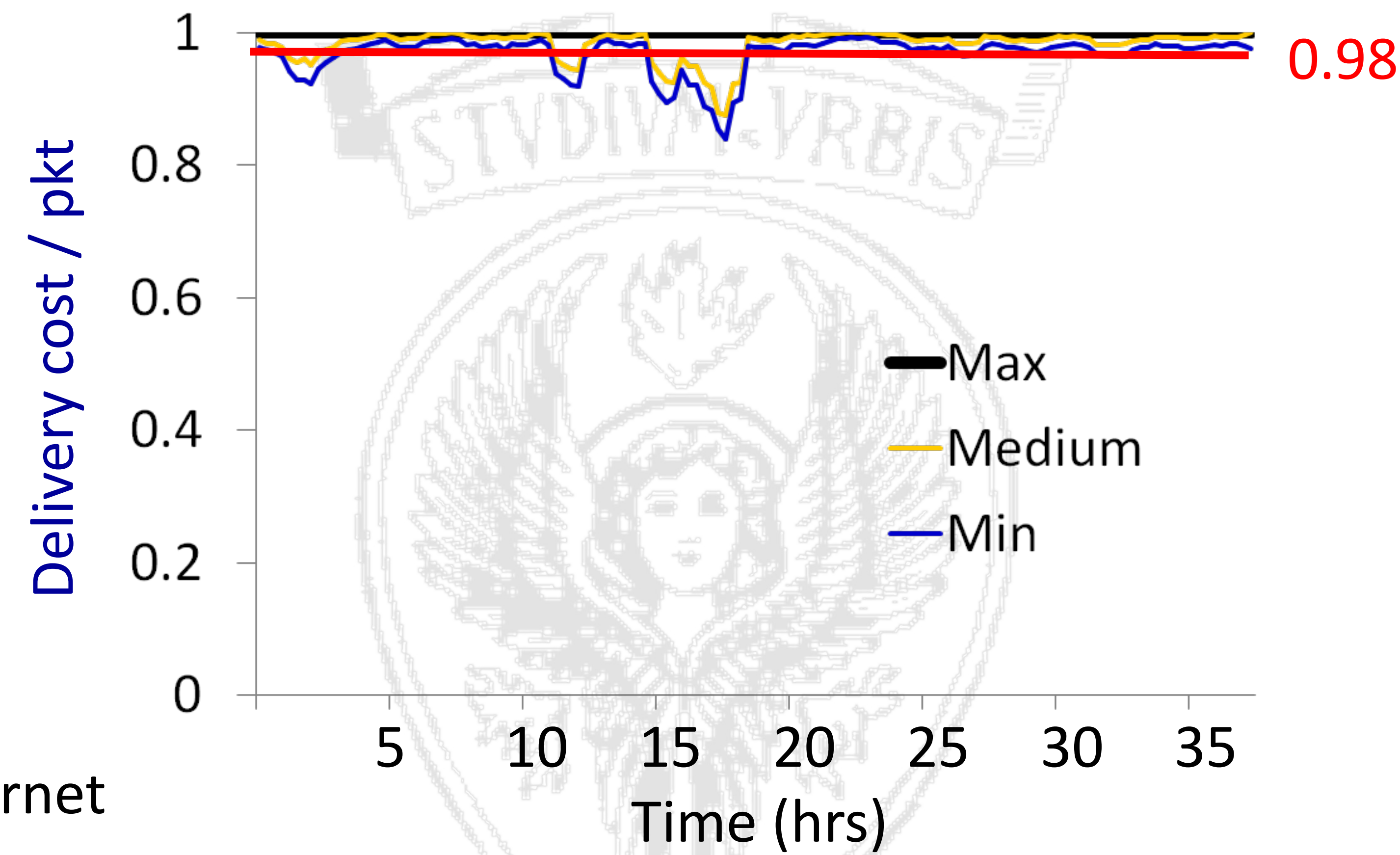


Twist



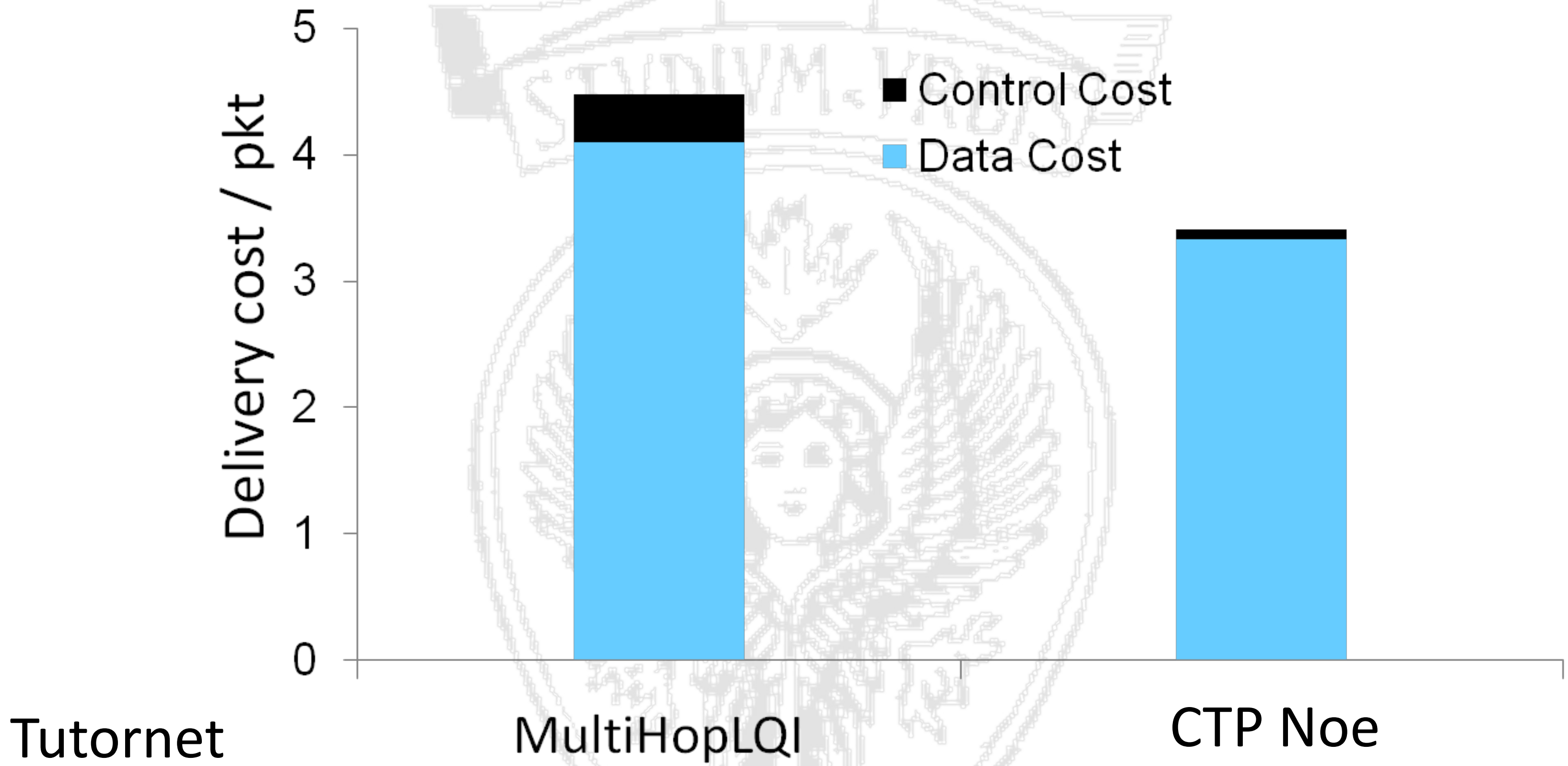
Mirage





Tutornet

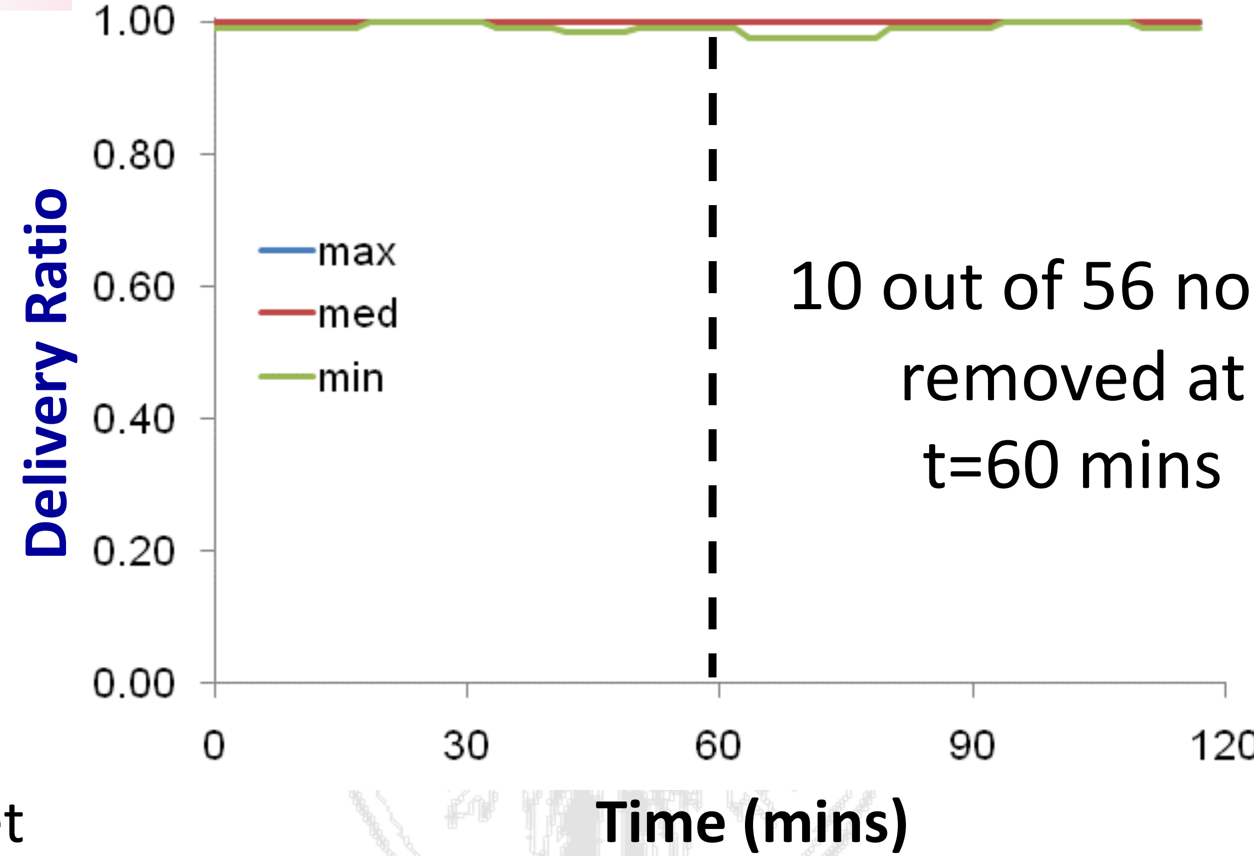
High delivery ratio across time
(short experiments can be misleading!)



Low data and control cost

Link Layer	Average Delivery	PL	Cost	Cost / 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%

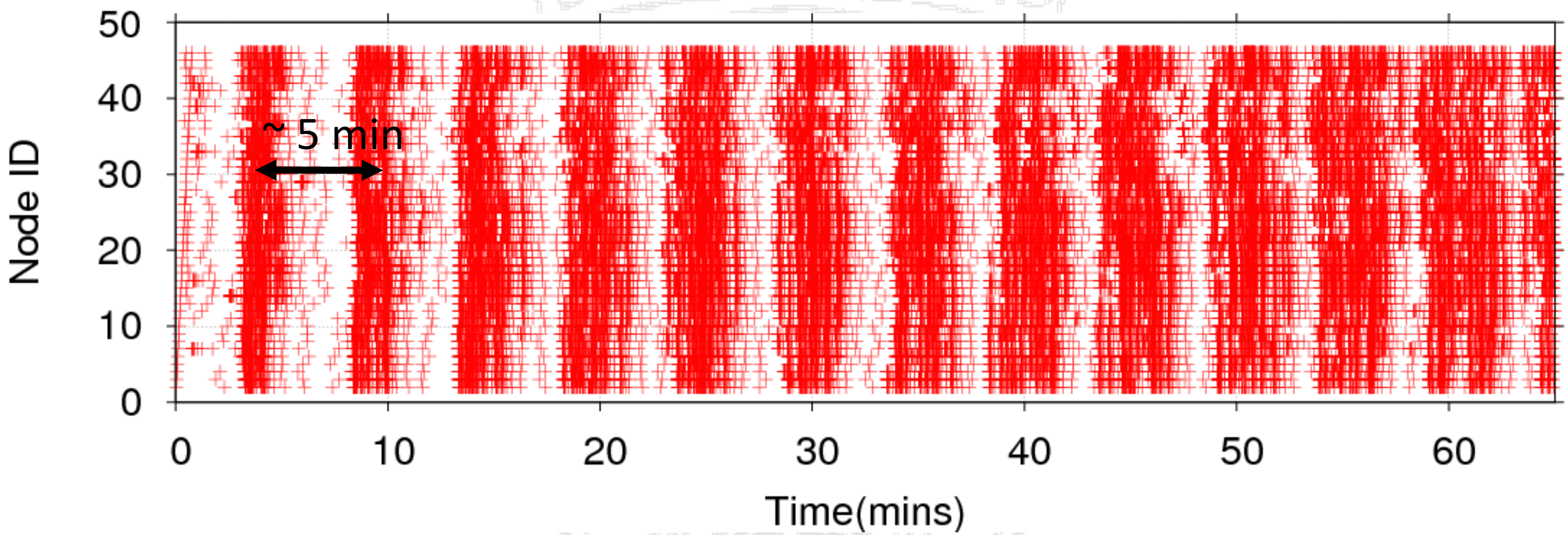
Low duty-cycle with low-power MACs



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)

Extensions of IEEE 802.15.4
Reading material:

De Guglielmo, Anastasi, Seghetti "From IEEE 802.15.4 to IEEE 802.15.4e: A StepTowards the Internet of Things", advances in intelligence systems and computing, 2014, book chapter available at
https://www.researchgate.net/publication/289220698_From_IEEE_802154_to_IEEE_802154e_A_step_towards_the_Internet_of_Things

IEEE 802.15.4

- Reference PHY/MAC standard for IoT;
- Designed in the early times (2006) when IoT applications were still not deployed. Energy efficiency addressed.
- Good for some applications; but it does not fullfill the needs of some emerging industrial applications, where timeliness, reliability, robustness can be as important and which may demand for:
  - Real time guaranteed exchange of information, (e.g., in factory automation applications which motivated different standards promoted by industries such as WirelessHART, ISA100). Timeliness requirements can go from guaranteed latency below few msec (factory automation) to guaranteed latency within few minutes (asset control) but in any case requires a change of MAC.
  - Resilience to interference (e.g., through frequency hopping)
  - Ability to increase capacity (e.g., through multi-channel solutions).

IEEE 802.15.4

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  - Resilience to interference (e.g., through frequency hopping)
  - Ability to increase capacity (e.g., through multi-channel solutions).
- After a decade of research, after industrial needs identification, emergence of other standards to fullfil such needs, IEEE 802.15.4 working group has released in 2016 an extension of the standard which incorporates some of these ideas.
- Note: IEEE 802.15.4 working group is active. Standards evolve over time.

IEEE 802.15.4

- MAC used in the first version of the standard: CSMA/CA based
- Limits:
  - No delay guarantees;
  - No resilience to interference (lack of frequency hopping support);
  - Not ideal MAC in high traffic scenarios;
  - Some energy optimizations to support tree topologies not explicit/subject to interpretation to what could be a standard compliant IEEE 802.15.4 solution—despite possible and available; needed to be better clarified).
- For applications not properly supported IEEE 802.15.4 (2012, 2016) has provided extensions targeted for specific application domains. General objectives of such extensions:
  - Low energy (LE): It allows a device to operate with a very low duty cycle (e.g., 1%or below),while appearing to be always on to the upper layers.
  - Enhanced Beacons (EB). Extended Beacons are an extension of the 802.15.4 beacon frames. They allow to create application-specific beacons, by including relevant information elements depending on the needs of specific variants of IEEE 802.15.4e.
  - Multipurpose Frame: flexible frame element.
  - MAC Performance metrics, allowing e.g., to provide link quality information to upper layers;
  - Fast association. Changes association procedure which was trading off energy for latency in case of applications which require fast association.

IEEE 802.15.4e variants

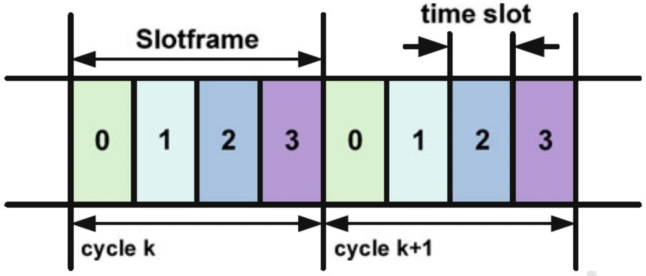
- Radio Frequency Identification Blink (BLINK) mode supports effective ID exchange for sake of item/people identification, location, and tracking
- Asynchronous multi-channel adaptation (AMCA) supports dynamic multi-channel use in distributed beaconless networks
- Deterministic and Synchronous Multi-channel Extension (DSME) supports time-critical applications for large networks in beacon-enabled PANs
  - Guaranteed Time Slot mechanism included in basic IEEE 802.15.4 has limitations, supports only 7 slots per frame, does not allow to use multiple channels
  - DSME enhances GTS by forming a multi-superframe and using multi-channel operation. A multi-superframe is a cycle of superframes, where each superframe includes the beacon frame, the CAP (only for the first superframe in the cycle) and the GTS. A pair of nodes wakes up at a reserved GTS slot to exchange a data frame and an ACK frame.

IEEE 802.15.4e variants

- The Low Latency Deterministic Network (LLDN) supports commercial and industrial applications requiring low and deterministic latency. Large number of actuators and sensors monitoring and controlling an operation. 100 of sensors/actuators need to be supported. Guaranteed latency below tens of msec.→Multi-channel extension (the PAN coordinator has multiple transceivers and can simultaneously tx over multiple channels), slotted beacon-enabled frames, star topologies, shorter slots/packets, short 8-bit addresses.
  - Beacon time slot, management time slot, base timeslot (some dedicated and some shared-in shared CSMA/CA contention), cumulative ACK sent by PAN coordinator at the superframe level)
- Time Slotted Channel Hopping (TSCH) supports industry applications by combining slotted access, multi-channel support and frequency hopping.
  - Topology independent;
  - Supports increased network capacity, high reliability and predictable latency, while enabling low duty cycling.

IEEE 802.15.4e TSCH

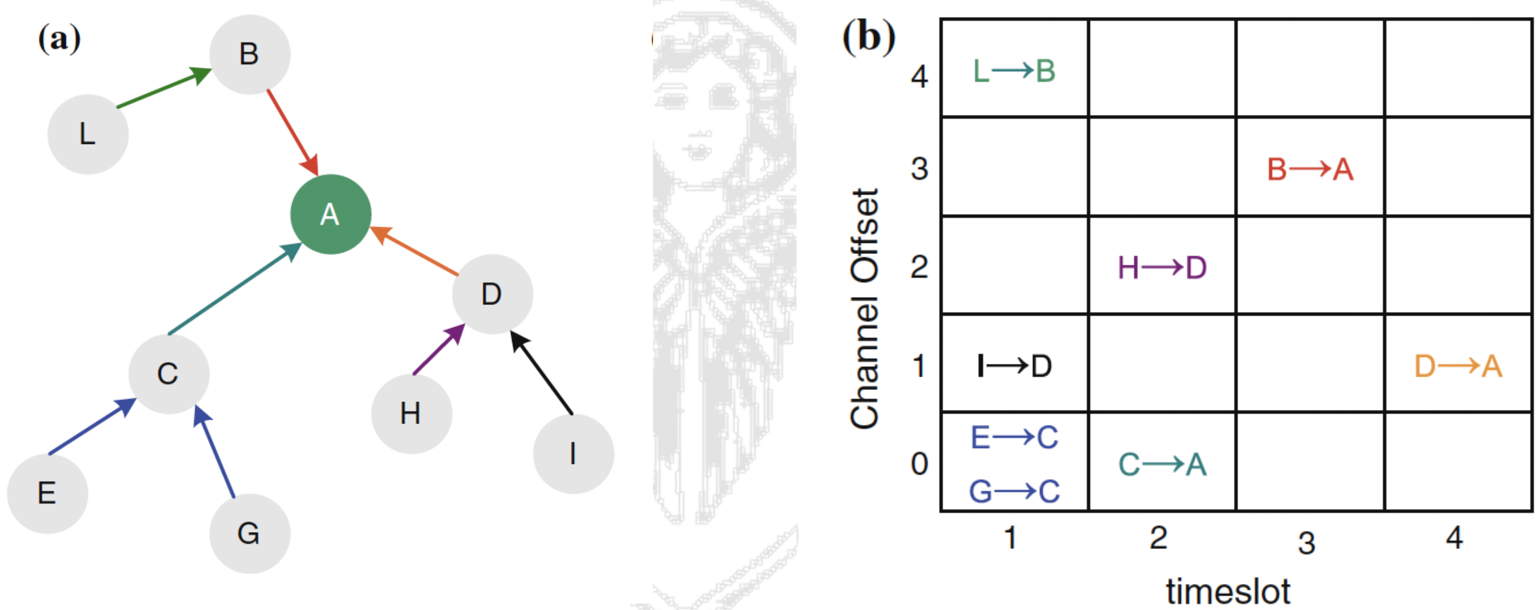
- Nodes synchronize on a periodic slotframe consisting of x timeslots (case x=4 in the figure).



- Each timeslot allows a node to send max size data and receive ack (if no ack received retransmission in the next time slot)
- A channel is identified by slot associated for bidirectional communication and frequency offset.
- Concurrent transmissions on multiple channels (using different frequencies) is allowed.
- Some frequencies maybe blacklisted if they are experiencing low link quality.

IEEE 802.15.4e TSCH

- In the figure the case of application of TSCH with a slotframe made of 4 slots and 5 frequency (out of max 16) used is shown. (it shows also shared channels, in case of shared channels and a collision the backoff is in terms of number of shared links to wait before attempting again)



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Building the IoT

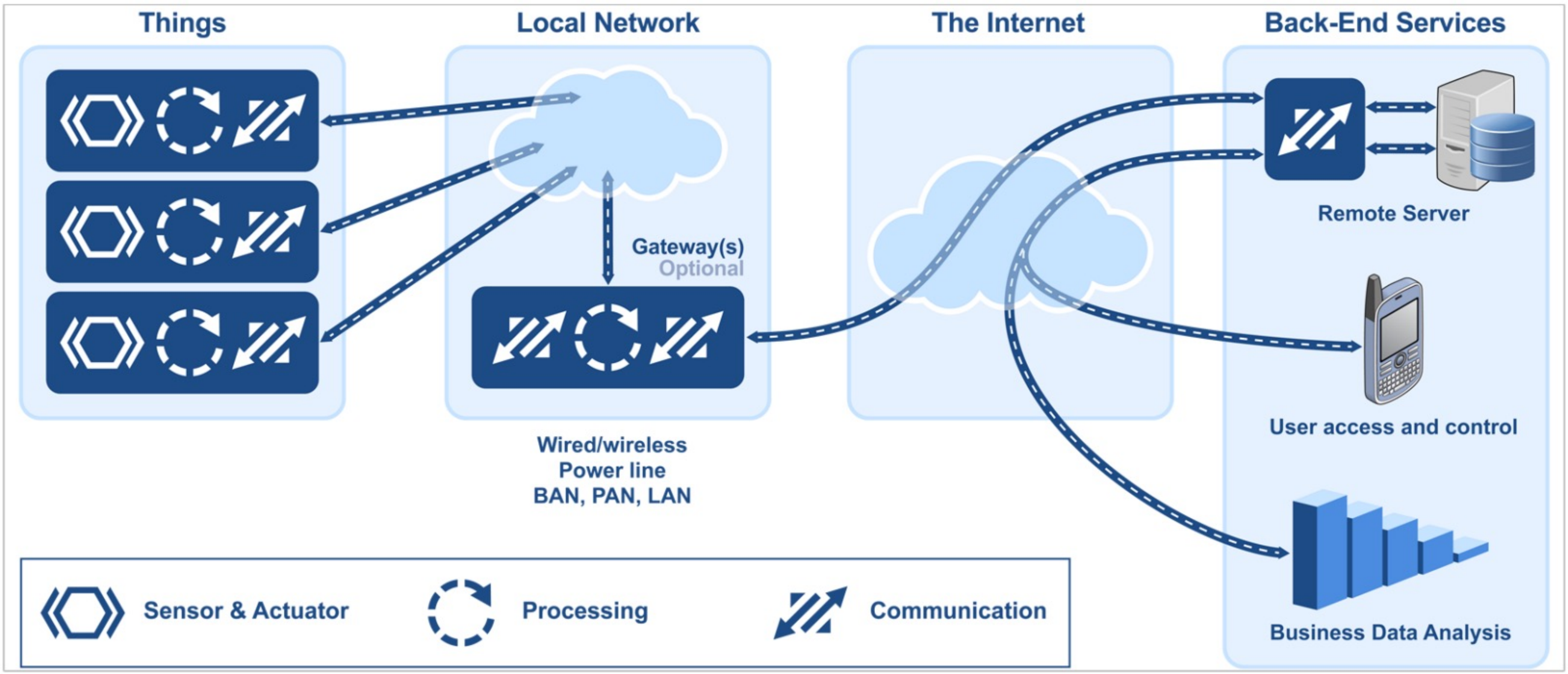
Internet of Things a.a. 2020/2021

Un. of Rome "La Sapienza"

Chiara Petrioli†

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

Current Scenario



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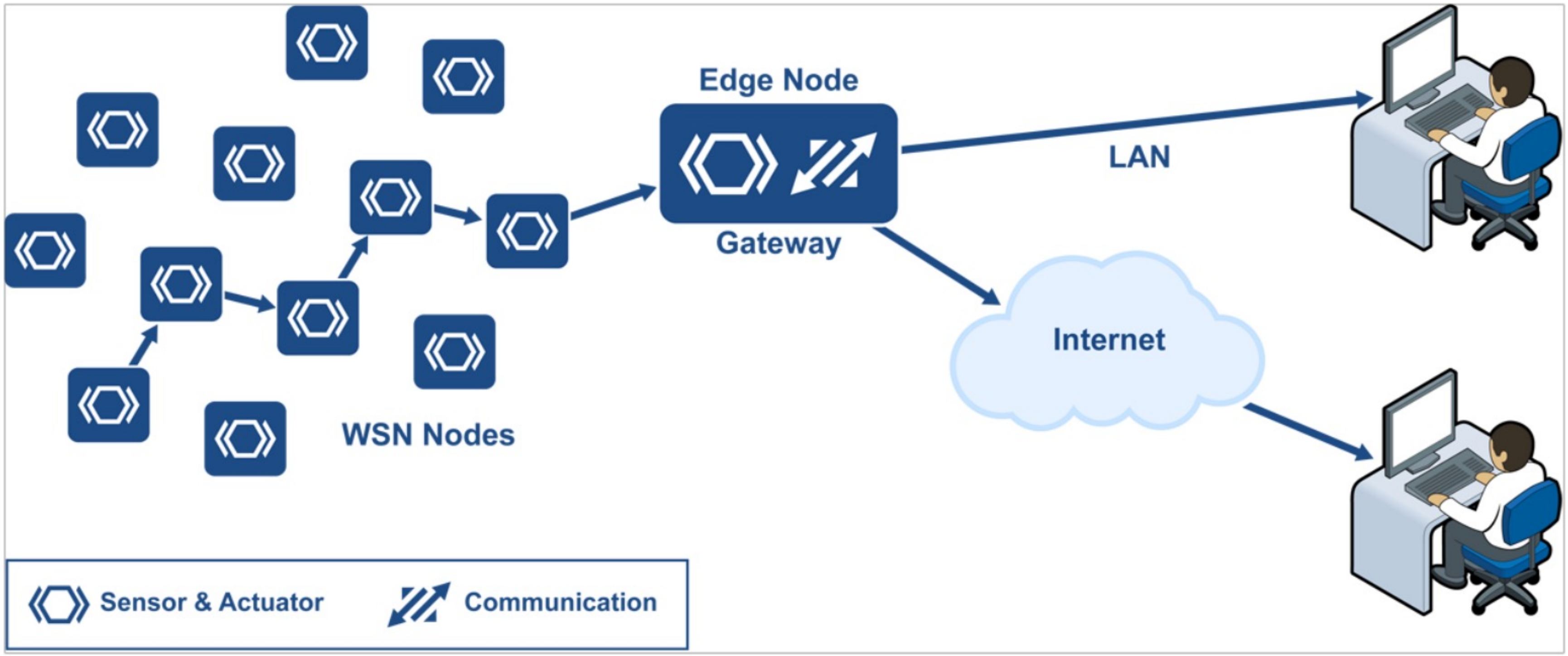
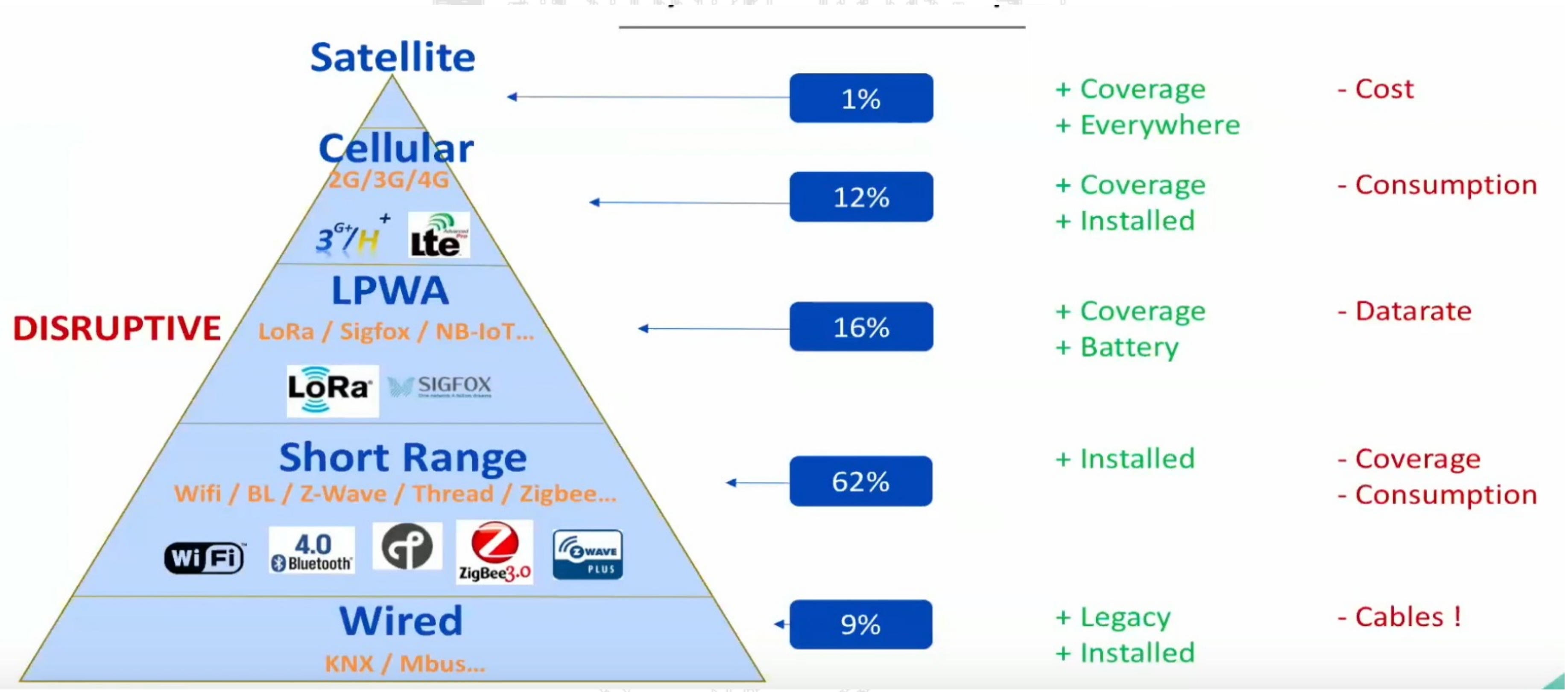
Current Scenario



Current Scenario



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Current Scenario

Requirements

Low power,

Miniaturization,

Indoor/outdoor

What to sense,

Data Analysis capability,

Data rate, range,
security support, …

→ Embedded platform selection or design

Requirements

Area to cover, operational conditions, possible topologies of deployment

Operational states

State x: What to sense, where to sense, alarm thresholds, frequency of reporting,…

Required system management capabilities

Required data analysis capability, data access control, security requirements

…..

→

System architecture design

-Types of Nodes to develop (each with different capabilities) →system components

-Network Topology

--Comm. among system components: protocols, APIs

-Gateway elements

-Software Architecture Backend/Frontend

Useful methodologies

Idea → [Proof/analysis]→Solution Simulation→Field Test

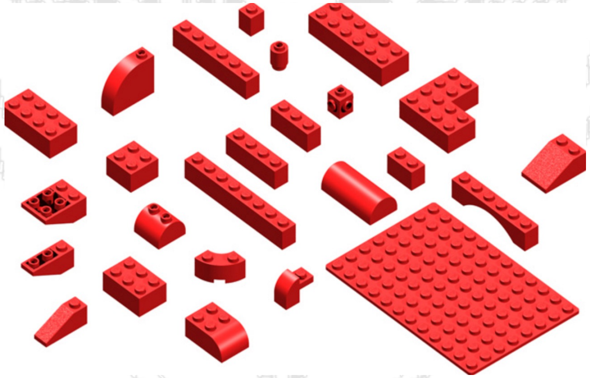
System Optimization

Useful methodologies

Idea → [Proof/analysis]→Solution Simulation→Field Test

System Optimization

What we are doing…providing you with the



to combine, extend, in order to come up with innovative solutions

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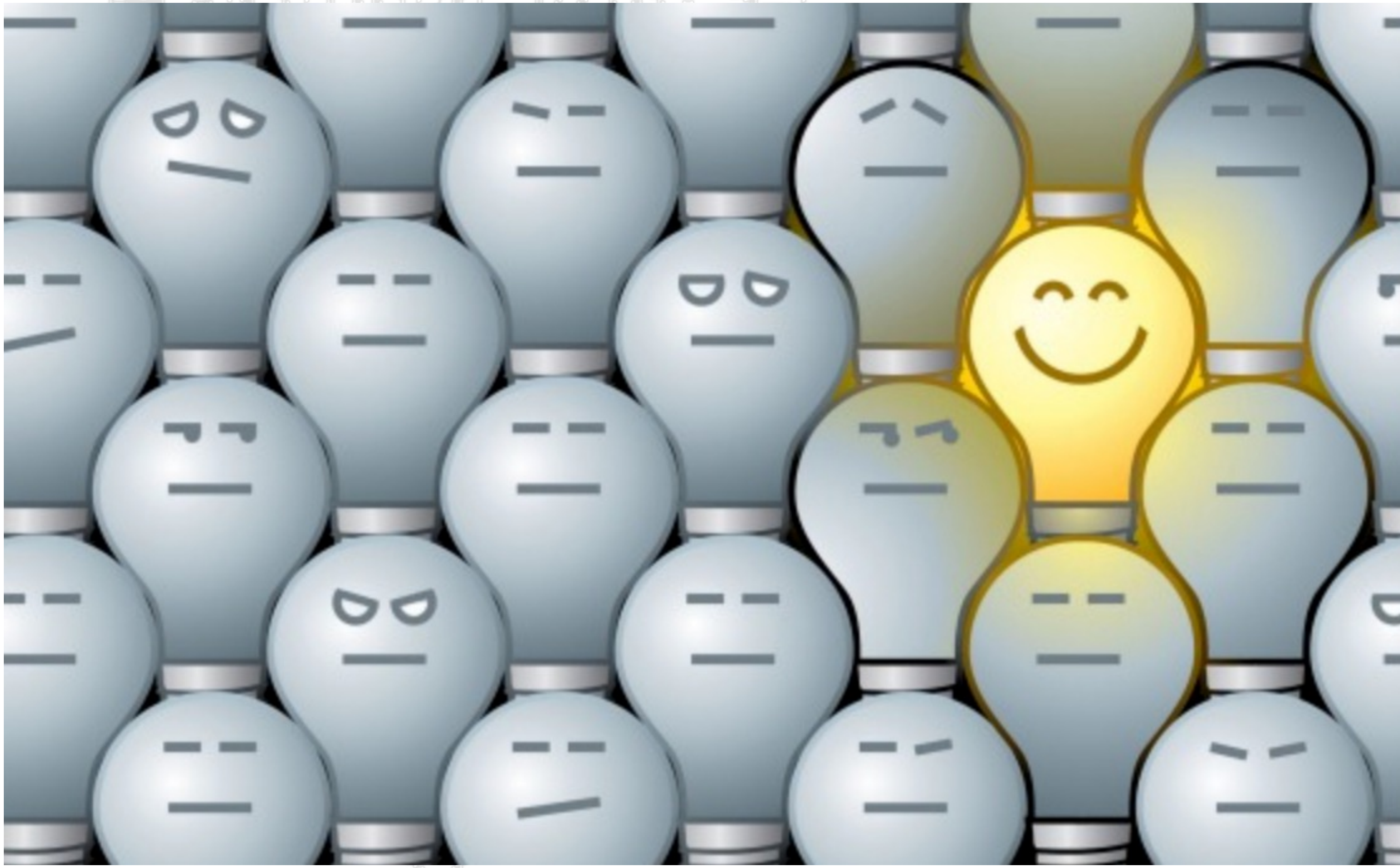
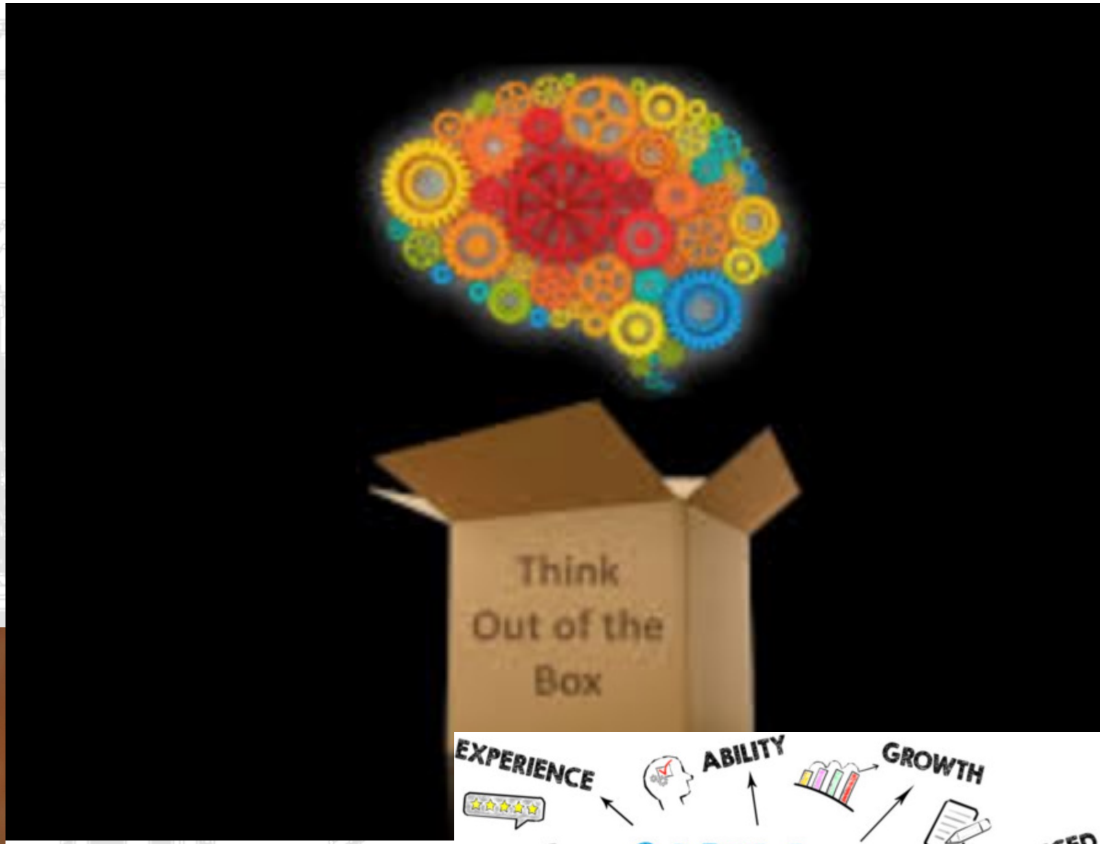
Innovation Training

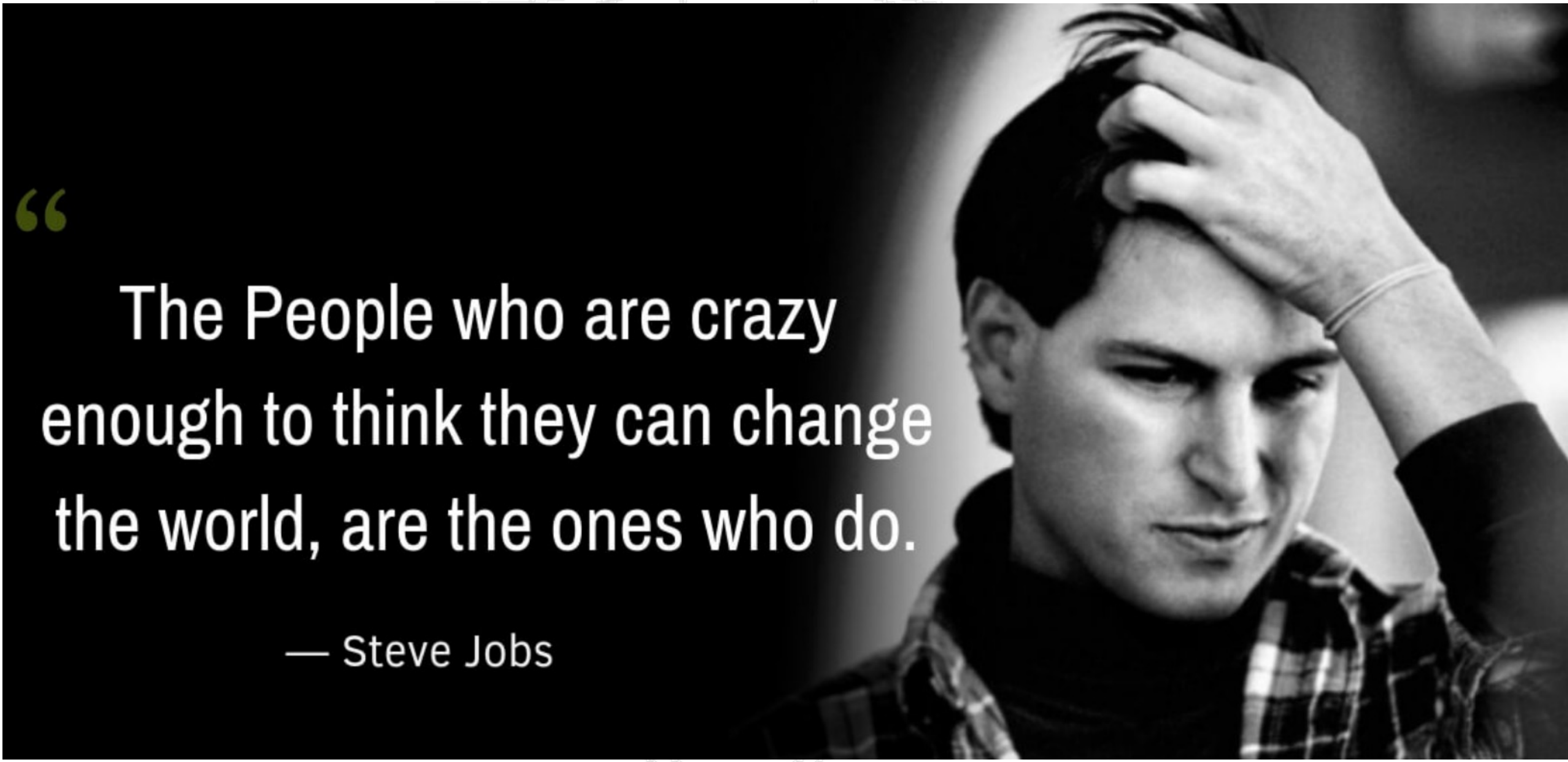


IoT Innovation

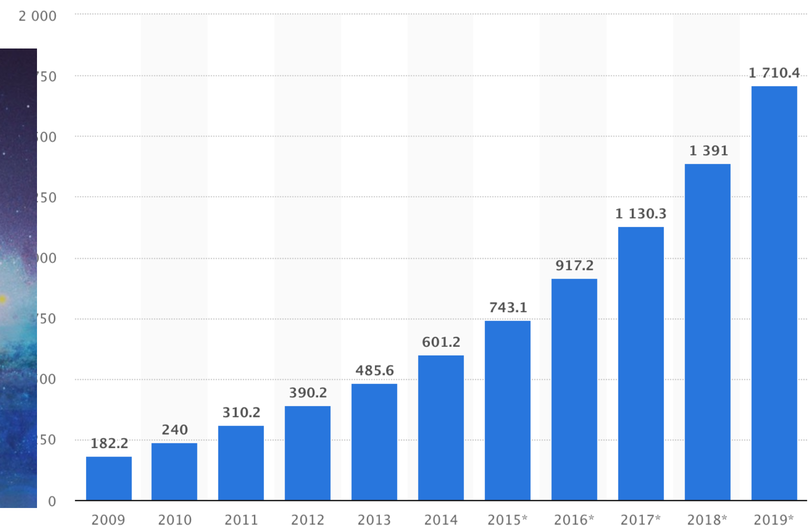
Innovation Training




INNOVATION IS A STATE OF MIND


"
The People who are crazy
enough to think they can change
the world, are the ones who do.
— Steve Jobs

Why on IoT ?


2 000
0
182.2
240
310.2
390.2
485.6
601.2
743.1
917.2
1 130.3
1 391
1 710.4
2009
2010
2011
2012
2013
2014
2015*
2016*
2017*
2018*
2019*

Market Sizes

- IoT - **The global IoT market is expected to have a compound annual growth rate (CAGR) of nearly 27 percent from 2018 to 2024.** Overall, the market is expected to grow to **$6.5 trillion** in 2024

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Market Sizes

- IoT - **The global IoT market is expected to have a compound annual growth rate (CAGR) of nearly 27 percent from 2018 to 2024.** Overall, the market is expected to grow to **$6.5 trillion** in 2024
- Today 500Bln
- What about other CS sectors?

- Cyber Security 124Bln
- AI and Machine Learning 24Bln
- Computer Graphics 32Bln
- NLP 3Bln

Innovation Training

- Additional opportunity for the best students (based on what you are interested in):
  - Attività formativa complementare (extra 6 credits activity can be taken following up on a project under my supervision);
  - Borse di studio per attività di ricerca;
  - Possibility to attend a conf in the field;
  - Thesis.

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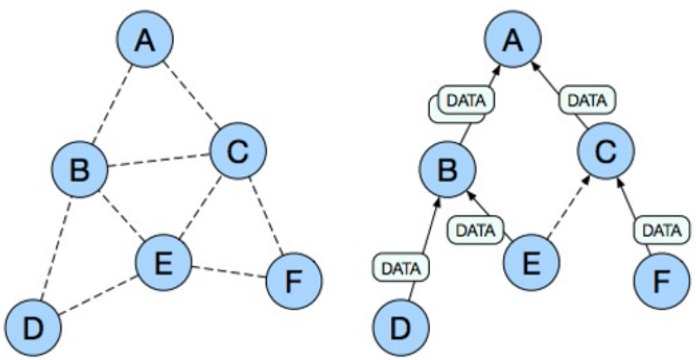
RPL, 2012
Material to read:

http://disi.unitn.it/~picco/papers/commag16.pdf

Routing in IoT

- 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



(a) A sample wireless network.

(b) Multipoint-to-point communication.

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) – rooted in the edge router
- 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 change over time…)
- Focus on energy constrained, secure solutions
- Routing supported across multiple types of link layers

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  - <Find links> or <Find t ttery operated nodes>
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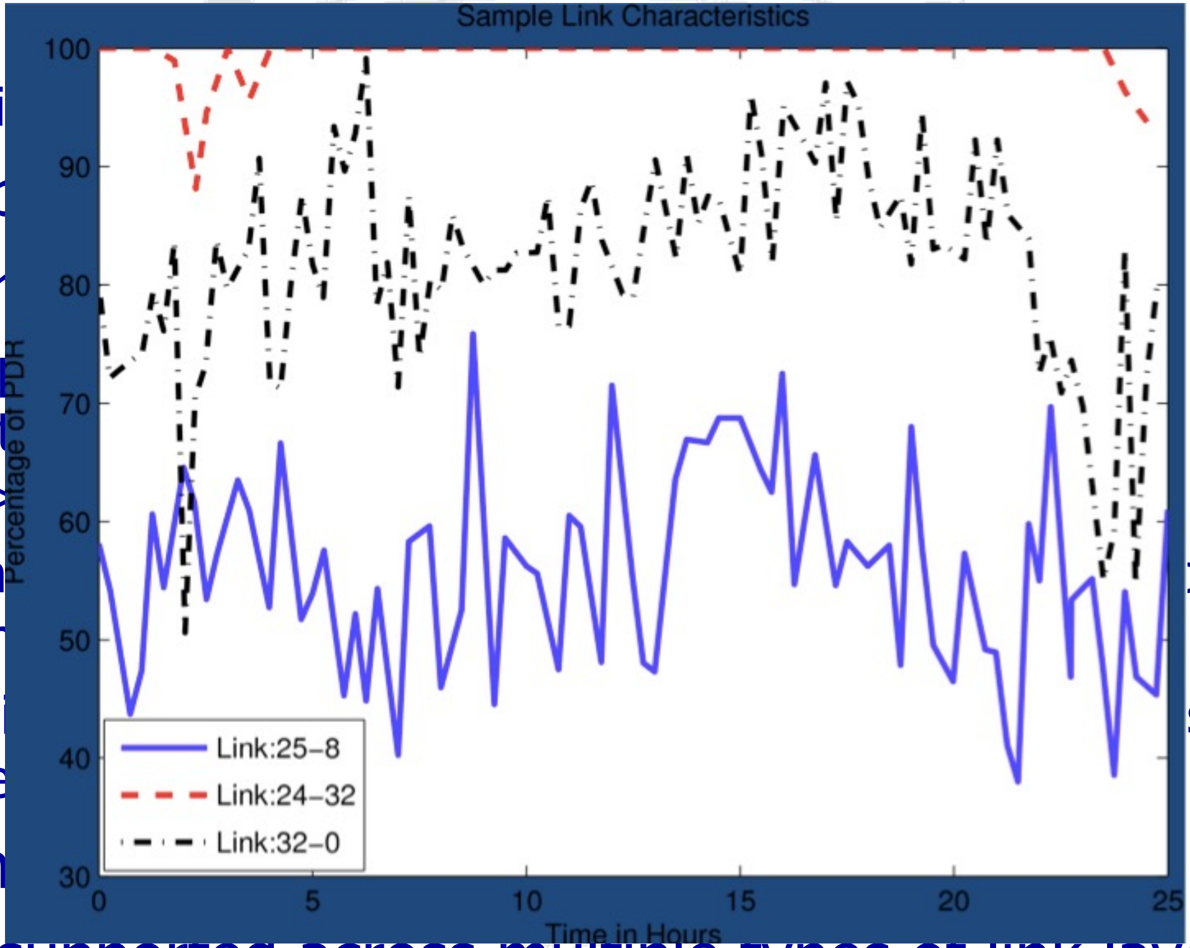
  - dynami s, all fast change
- Focus on



- Routing supported across multiple types of link layers

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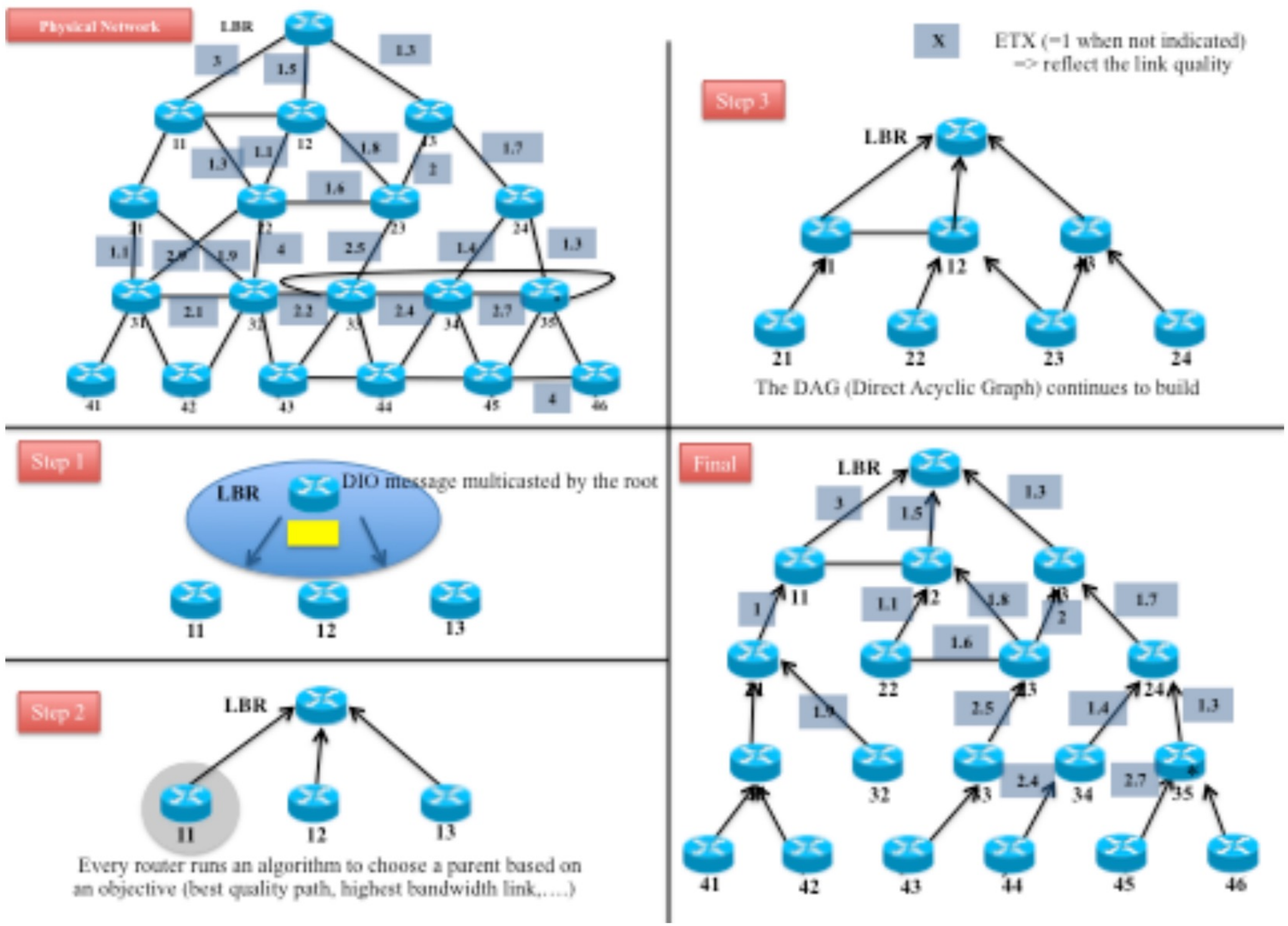
RPL– DODAG formation

- RPL specifies how to build a destination oriented acyclic graph (DODAG)
- Root (ER-LowPAN Border Router) sends a DIO (DODAG Information Object) message
- Neighbors of the root will listen to the DIO and decide whether to join DODAG
  – Each of their neighbors, upon receiving the DIO, selects its parent (according to a suitable metric) and –if it is configured as a router- reforwards the DIO.
  – Lead nodes do not reforward the DIO

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

RPL– DODAG formation



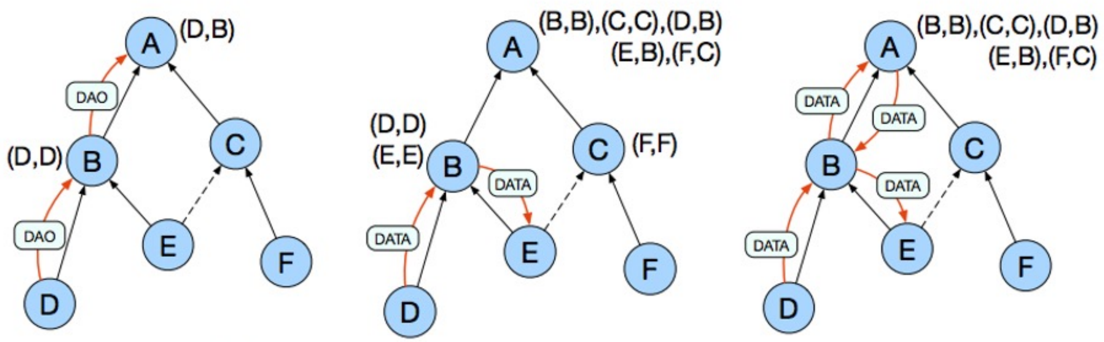
RPL -- How to multicast messages

- Destination Advertisement Object (DAO)
- As a node joins the graph it sends a DAO to its parent (can also be solicited via a DODAG Information Solicitation message- This DIS message is used by the nodes to proactively solicit graph information)
- 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

DIS, DIO and DAO are new ICMPv6 control messages to exchange graph related information.

RPL -- How to multicast messages

- 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
  - **In case we operate in non-storing mode the message goes till the rot that adds a source route and send it down to the final destination**



(c) Point-to-multipoint route construction: storing mode.

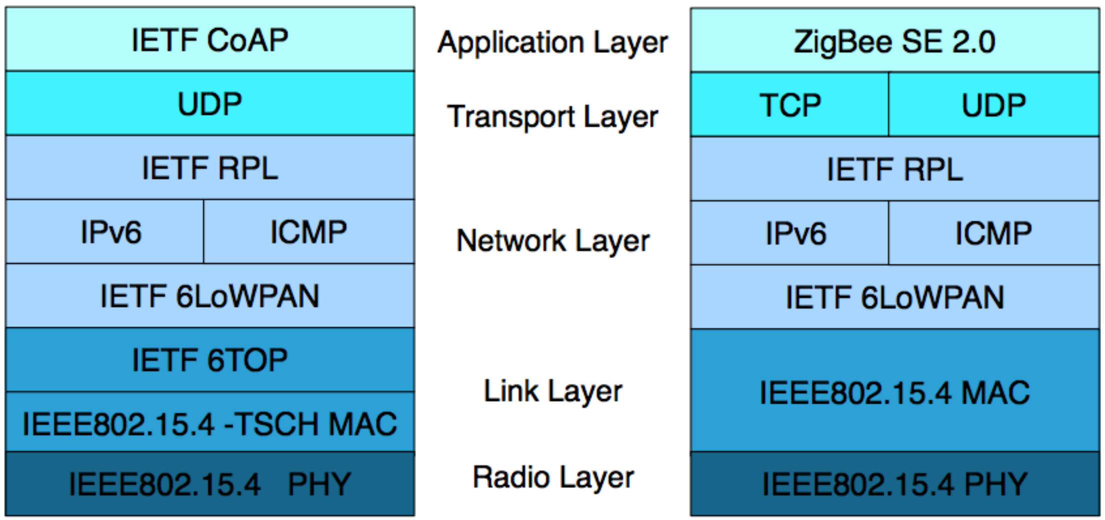
(d) Point-to-point communication: storing mode.

(e) Point-to-point communication: non storing mode.

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

6LowPan and RPL evolution

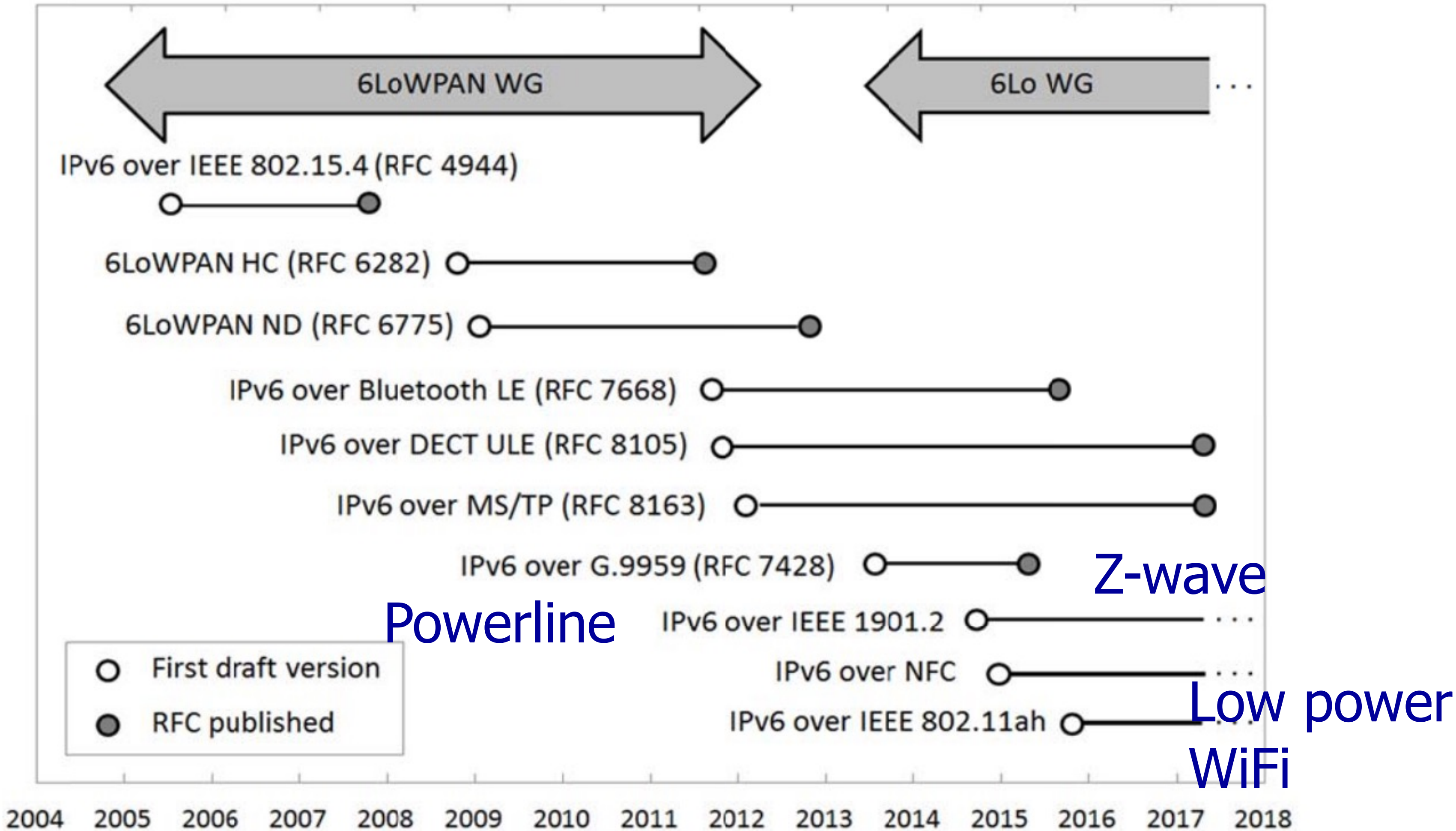


(a) IETF standardized stack. (b) ZigbeeIP stack.

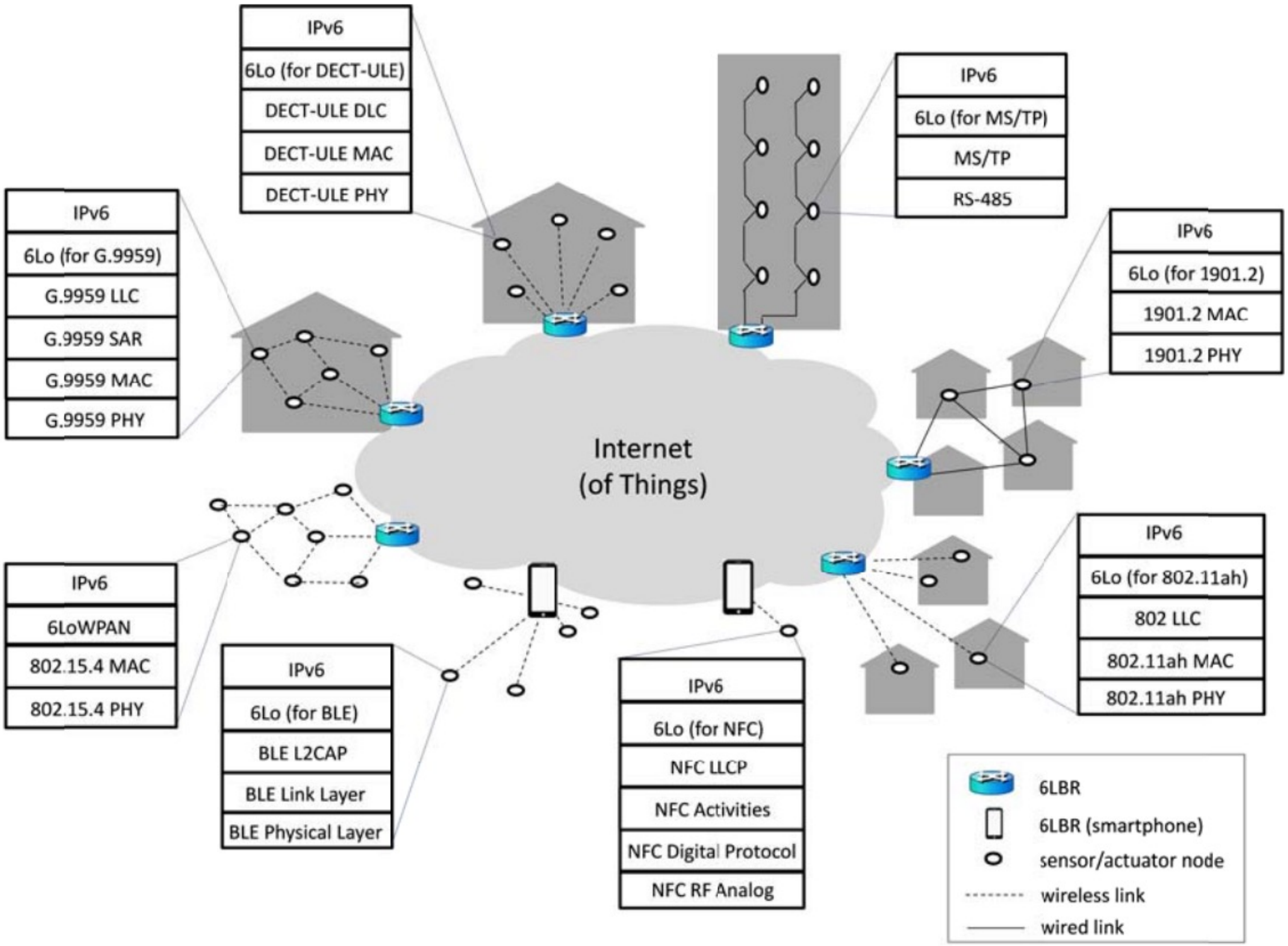
Further reading on 6Lo

https://www.recercat.cat/bitstream/handle/2072/355544/COMMAG-16-00534.R3__public.pdf?sequence=1

6LowPan evolution



6LowPan evolution



6LowPan evolution

		6LoWPAN	6Lo						
		IEEE 802.15.4	Bluetooth LE	ITU-T G.9959	DECT ULE	MS/TP	NFC	IEEE 1901.2	IEEE 802.11ah
Technology	Medium	Wireless	Wireless	Wireless	Wireless	Wired	Wireless	Wired	Wireless
	Frequency band (MHz)	868/915/2400	2400	868/915	1900	Base-band	13.56	< 0.5	< 1000
	Range (m)	10-100	10-100	100	< 300	1000	< 0.2	> 1000	< 1000
	Bit rate (kbit/s)	20/40/250	1000	9.6/40/100	1152	115.2	106/212/424	≤ 500	150-7800
	Max. single-frame L2 payload (bytes)	105	23	158	38	2032	125	215 (worst case)	7951
	ACKs and retries	Optional	Yes	Optional	Yes	No	ACK/NACK	ACK/NACK (optional)	Yes
	MAC mechanism	CSMA/CA, TDMA	TDMA	CSMA/CA	TDMA	Token passing	TDMA link initialization	CSMA/CA	CSMA/CA
	Address size (bits)	16/64	48	40	20/40/48	8	6	16/64	48
	L2 fragmentation	No	Yes	Yes	Yes	No	Yes	Yes	Yes
	Network topology	Star and mesh	Star	Mesh	Star	Multi-drop bus	Point-to-point	Star and mesh	Star
	Protocol stack	PHY/Link	PHY to App.	PHY/Link	PHY to App.	PHY/Link	PHY to App.	PHY/Link	PHY/Link
	Application	Generic purpose	Smartphone-centric	Home automation	Home automation	Building automation	Contactless exchange	Smart grid, home autom.	Sensors, backhaul
	Standardization organization	IEEE	Bluetooth SIG	ITU-T	ETSI	ANSI/ ASHRAE	NFC Forum	IEEE	IEEE
Adaptation Layer	Routing required	Yes	No	Yes	No	No	No	Yes	No
	Mesh under support	Yes	No	Yes	No	No	No	No	No
	Fragmentation	Yes	No	No	No	No	No	No	No
	6LoWPAN Header Compression	Yes	Yes (star topol.)	Yes (address adaptation)	Yes (star topology)	Yes (address adaptation)	Yes (address adaptation)	Yes	Yes (address adaptation)
	6LoWPAN Neighbor Discovery	Yes	Yes (no multihop)	Yes	Yes (no multihop)	Partially	With DHCPv6	DHCPv6 only	Yes (no multihop)
	Multicast	L2 broadcast	L2 unicast	L2 broadcast	L2 unicast	L2 broadcast	L2 broadcast	No	L2 multicast
	Privacy addresses	Not specified	Random IID	DHCPv6	Random IID	Random IID	Random IID	DCHPv6	Random IID
	L2 security used	Yes	Yes	Yes	Yes	No	No	Yes	Yes

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Protocols for EH-WSNs

Internet of Things, a.a. 2020/2021

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

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

Application scenarios

Smart Cities

Smart Environmen

Smart Water

Smart Metering

Security & Emergencie

Retail

Logístics

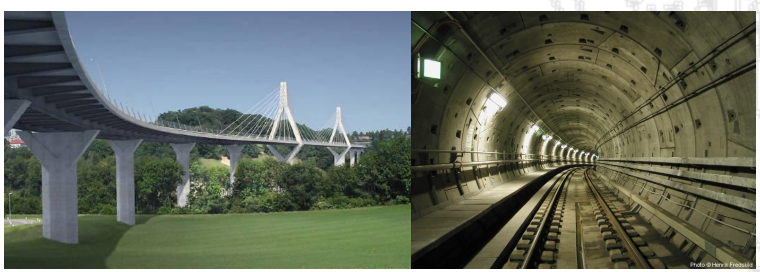
Industrial Control

Smart Agriculture

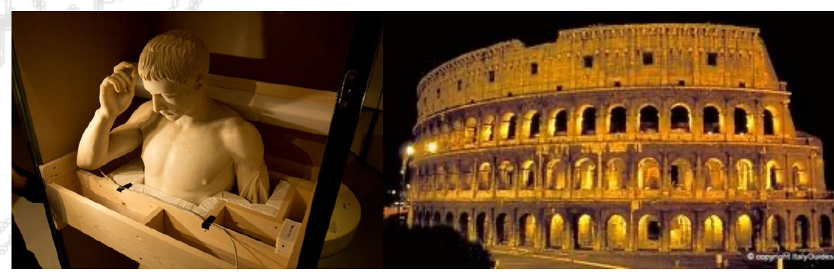
Smart Animal Farming

Domotic & Home Automation

eHealth



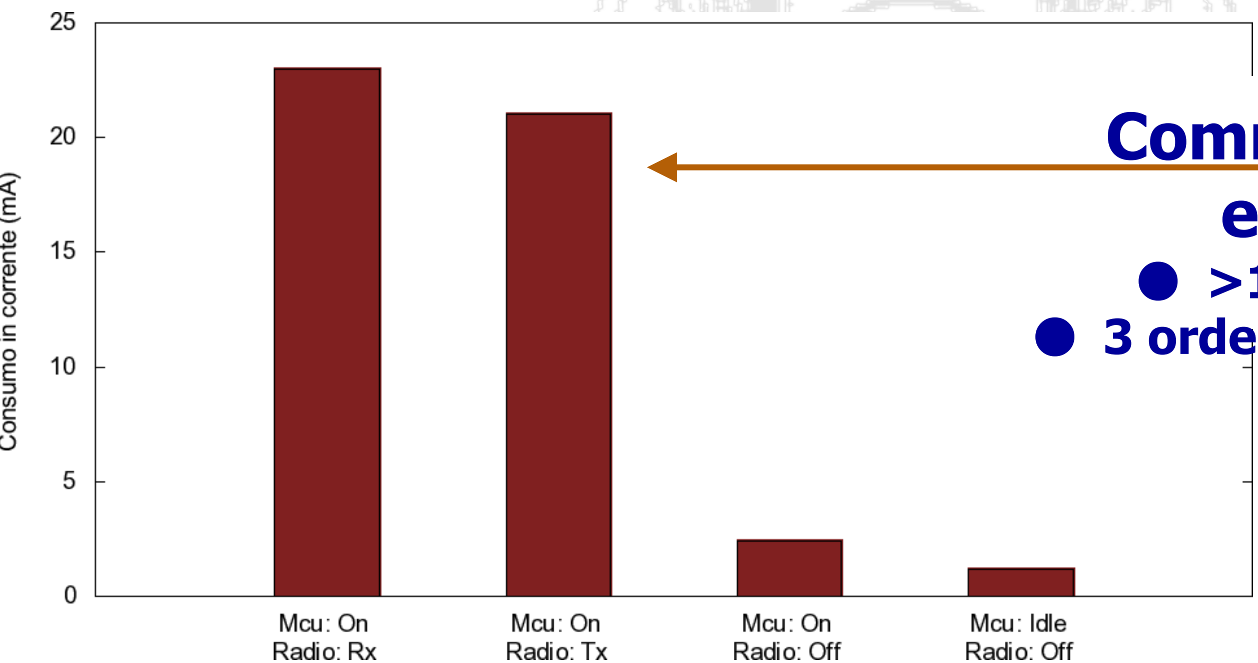
Structural health monitoring



Cultural Heritage

Energy Consumption

- In many applications (e.g., SHM) the network is required to run for **decades**
- Nodes are powered by batteries
  - Limited lifetime (a few days on 2xAA batteries if always on)

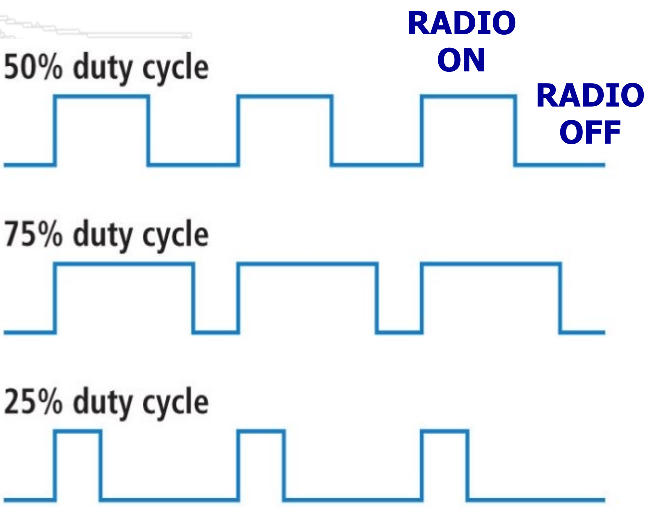


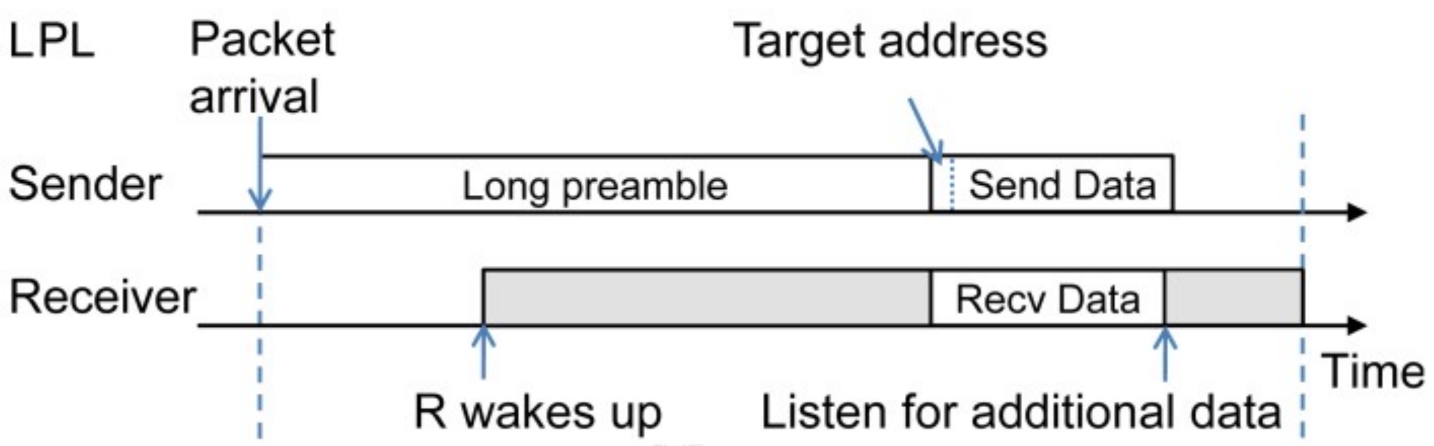
Communication is expensive!

- **>10x w.r.t. MCU on**
- **3 orders of magnitude w.r.t. sleep**

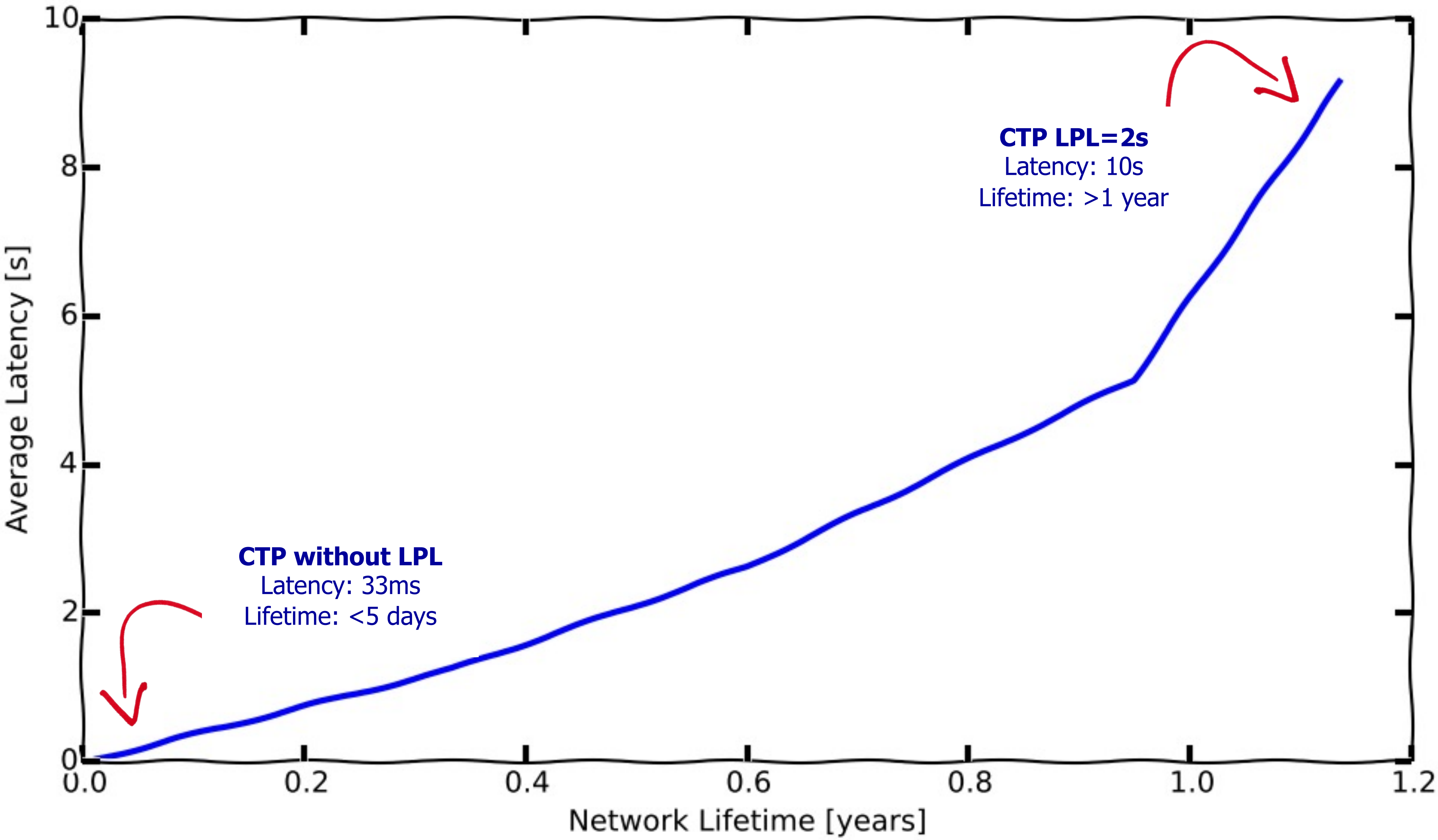
Standard Approach: Duty Cycling

- Periodically cycle the radio between ON/OFF states
  - OFF = save energy, but no communication
  - ON = high energy, but data can be transmitted and received

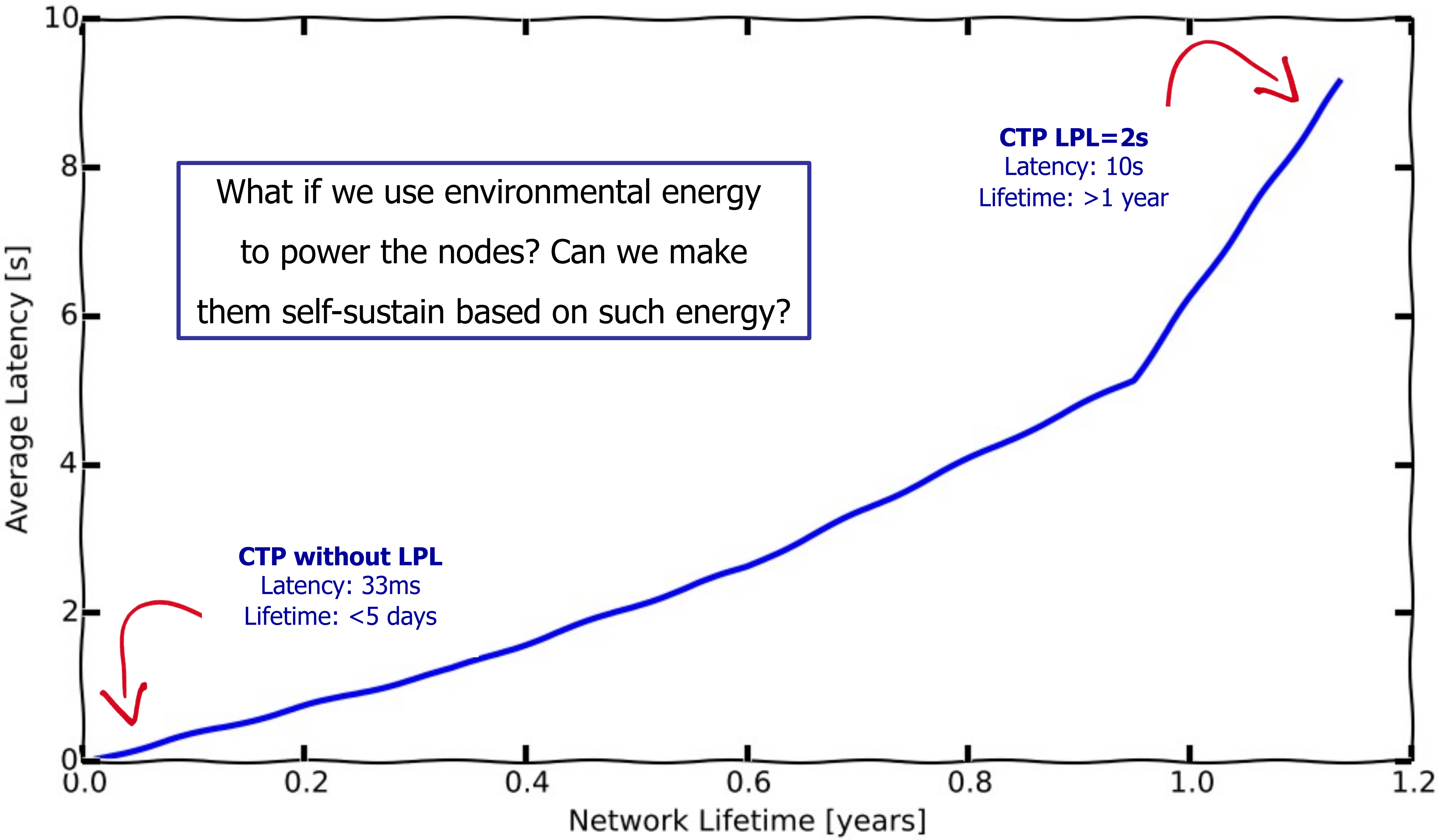




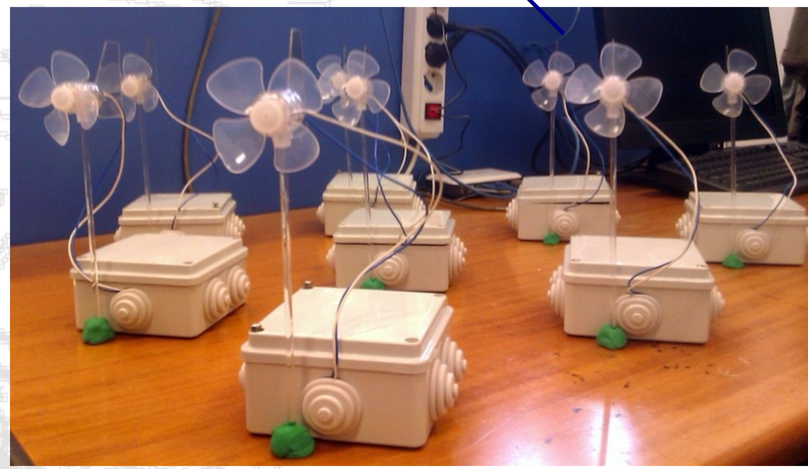
Latency vs. Energy Trade-off



Latency vs. Energy Trade-off

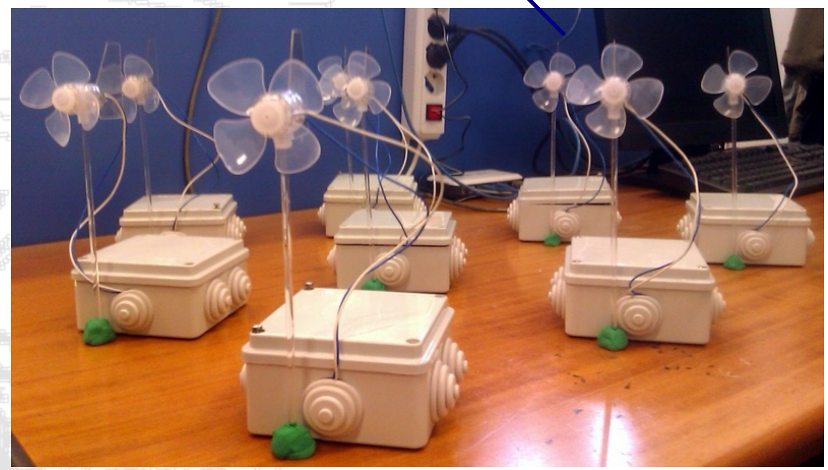


EH-WNS



- Pose the basis for very long lasting operation
- Energy Neutral protocols have been proposed for several applications
- Changes also what a WSN can do

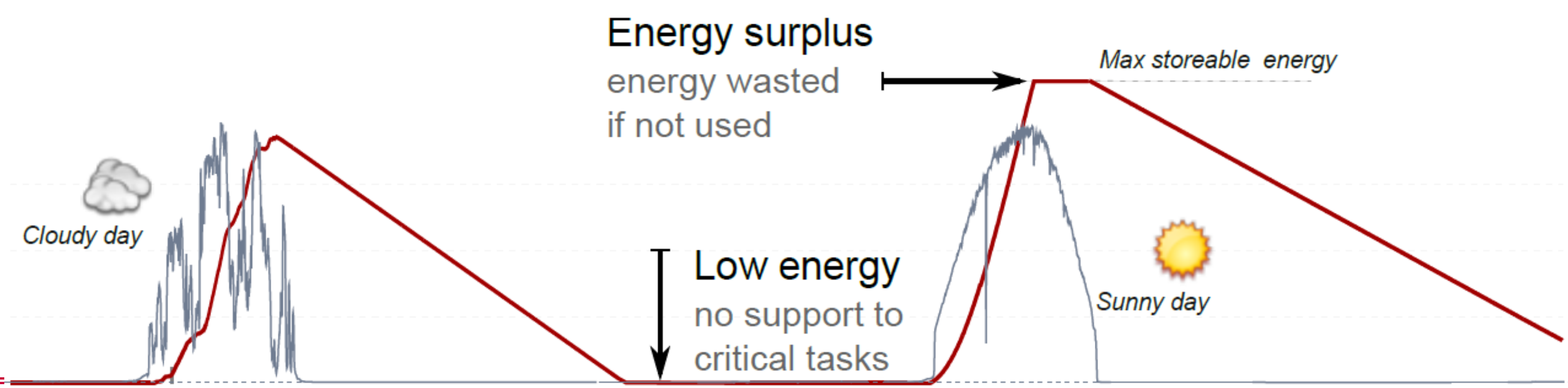
EH-WNS



- Pose the basis for very long lasting operation
- Energy Neutral protocols have been proposed for several applications
- Changes also what a WSN can do

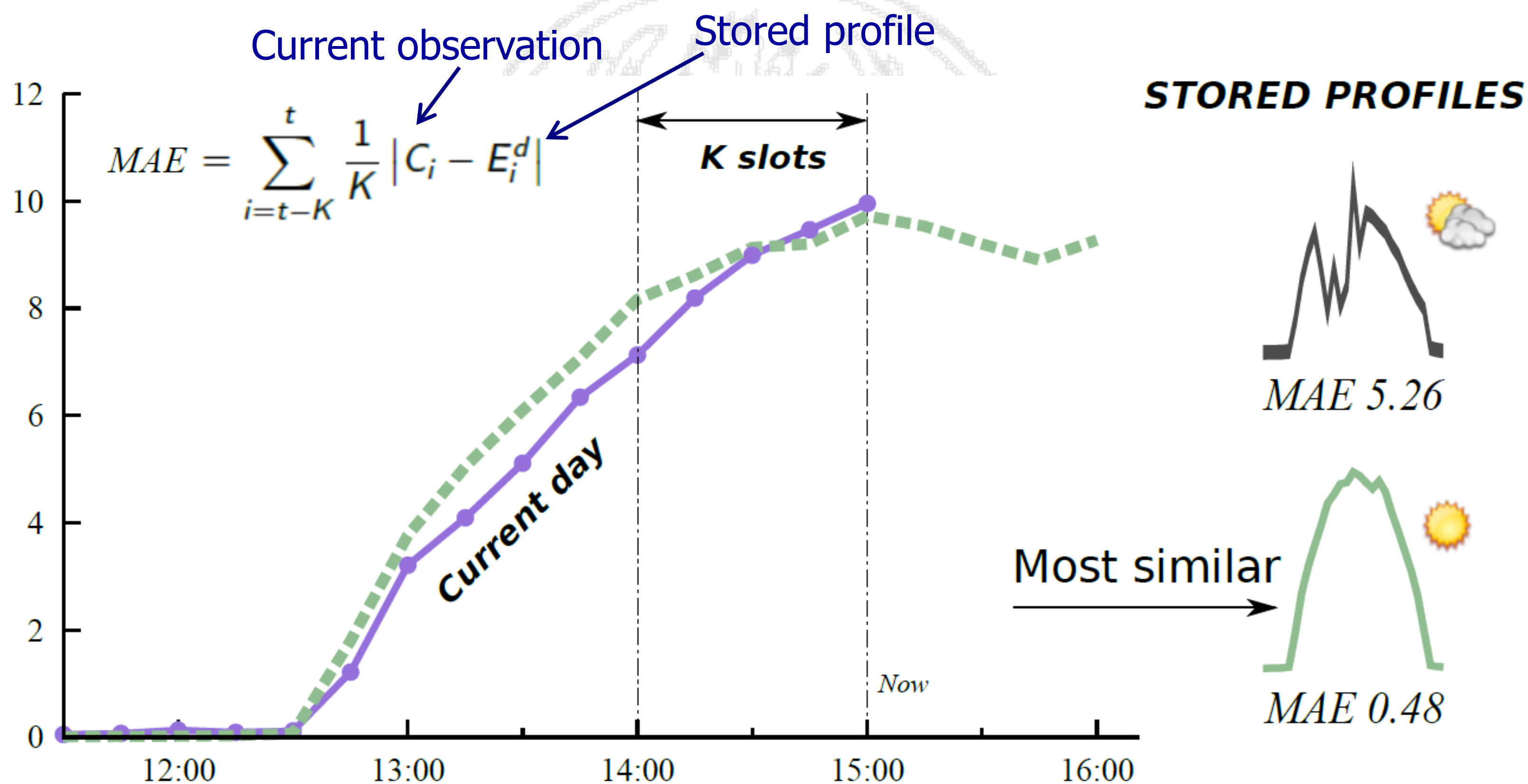
Why energy predictions?

- Energy predictions to mitigate uncertain energy availability (crucial for system planning)
- Plan energy usage in advance: **proactive** vs reactive energy allocation
- Exploit available energy at best:
  I. Minimizing the likelihood of running out of energy and missing high priority tasks
  II. Minimizing the waste of energy (energy buffers are limited in size and time)
  III. Enable operations which were not considered feasible



Pro-Energy in a nutshell

- Keep track of energy profiles observed during D typical days
- Store traces representative of different weather conditions (sunny, windy, ...)
- Predict future energy intake by looking at the most similar stored profile



Pro-Energy in a nutshell

$$\hat{E}_{t+1} = \alpha \cdot C_t \; + \; (1-\alpha) \cdot E^d_{t+1} \qquad (2)$$

where:

- $\hat{E}_{t+1}$ is the predicted energy intake in timeslot $t+1$ of the current day;
- E^d_{t+1} is the energy harvested during timeslot $t+1$ on the stored day d;
- C_t is the energy harvested during timeslot t on the current day C;
- α is a weighting factor, $0 \leq \alpha \leq 1$.

The weighting parameter, α, allows to combine the value reported in the stored profile with the current energy observation, i.e., the energy observed in the last slot, C_t.

Medium Term Energy Predictions

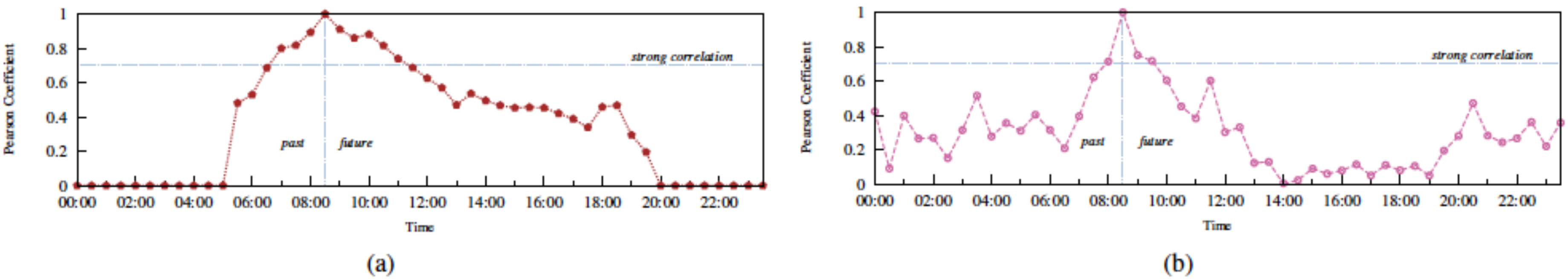


Figure 2. Pearson autocorrelation coefficient for (a) solar ORNL Dataset and (b) wind Bologna Dataset.

$$\gamma_i = \begin{cases} \alpha \cdot \left(1 - \frac{i-1}{G}\right), & \text{if } i \leq G \\ 0 & \text{if } i > G \end{cases} \qquad \forall i, 1 \leq i \leq F$$

where:

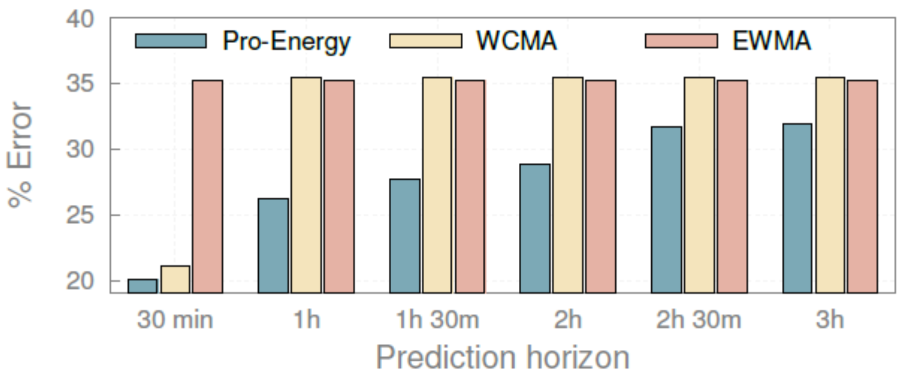
- α is the weighting factor defined in Equation (2);
- i is the i^{th} timeslot in the future, with respect to the current slot, t;
- G is the number of timeslots in the future which show a correlation above a given threshold with timeslot t;
- F is the number of future timeslots for which Pro-Energy is delivering energy predictions.

Medium term energy prediction estimation

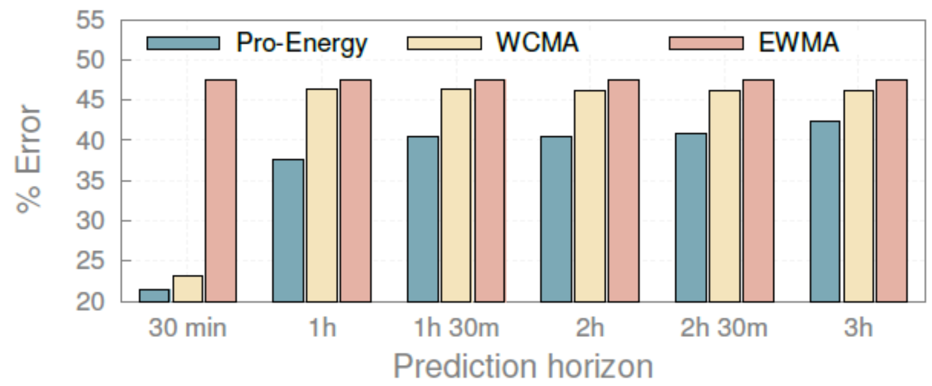
$$\hat{E}_{t+i} = \gamma_i \cdot C_t \; + \; (1 - \gamma_i) \cdot E^d_{t+i}$$

Pro-Energy accuracy

Solar



Wind



Solar: Pro-Energy performs up to **75%** better than EWMA and **60%** better than WCMA

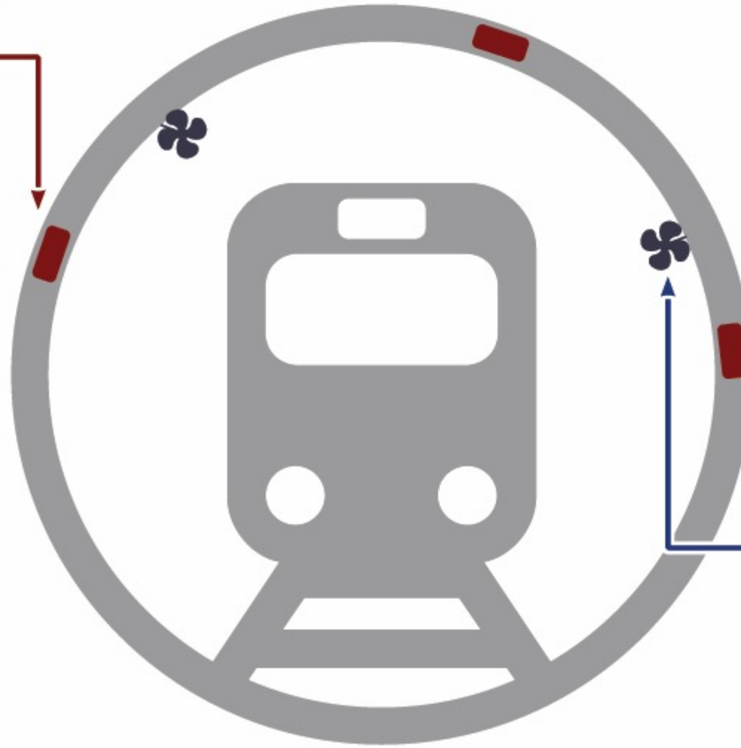
Wind: Pro-Energy performs up to **55%** better than EWMA and **10%** better than WCMA

Rome underground testbed

Vibrating Wire Strain Gauges

Monitor concrete and steel deformations to evaluate stability of the underground tunnel

SISGEO OVK4200VC00
Dedicated interface board for TelosB mote
Energy consumption: 720 mJ



Micro wind turbines

Energy harvesting from wind generated by trains

Why air-flow energy harvesting?

- SHM sensors are power-hungry
- required lifetime of decades or more
- battery-powered WSNs last only a few years

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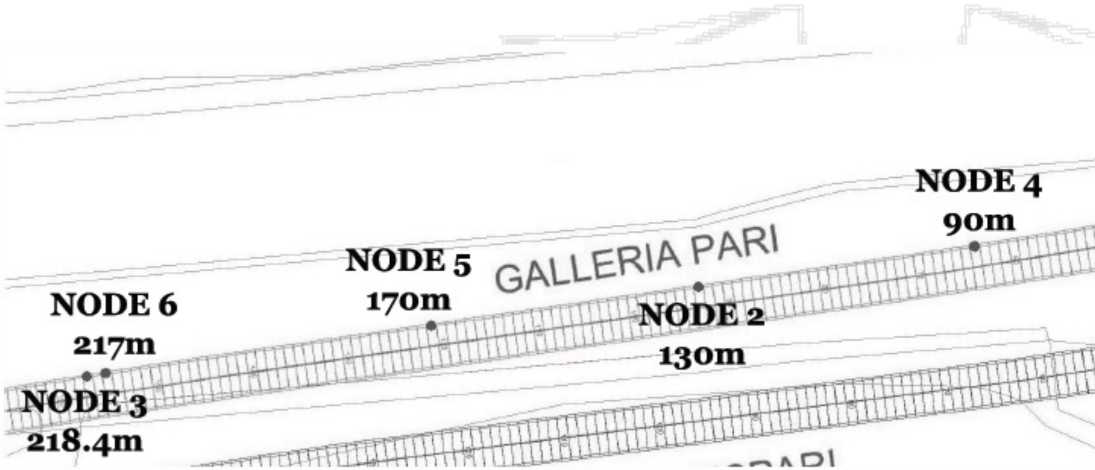
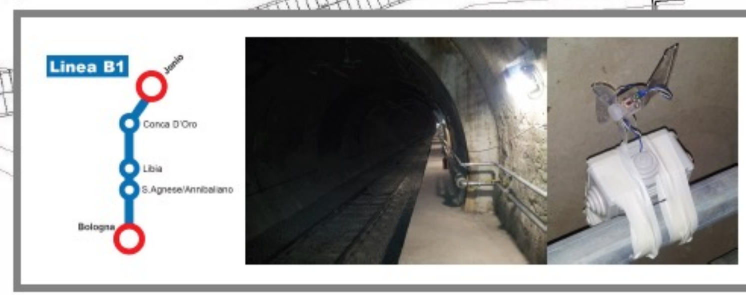
In-field air-flow data collection



Site plan courtesy of Roma Metropolitane and Tre Esse Engineering (FP7 project GENESI).



220 meter of instrumented tunnel

6 energy-harvesting nodes

33 days of data collection

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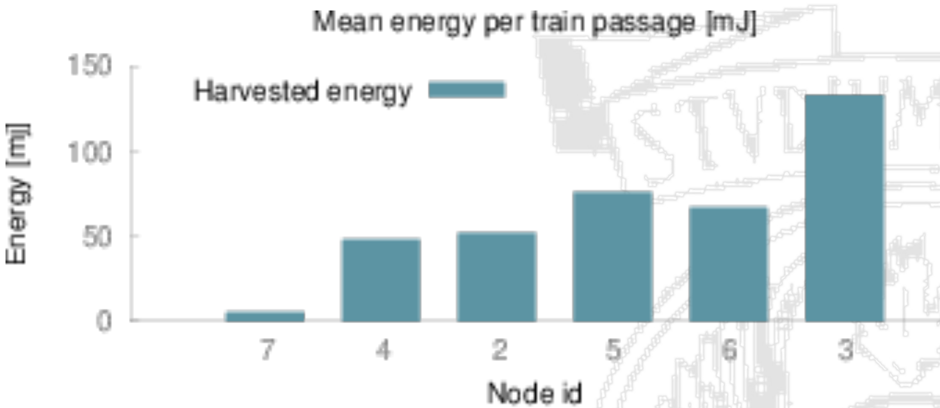
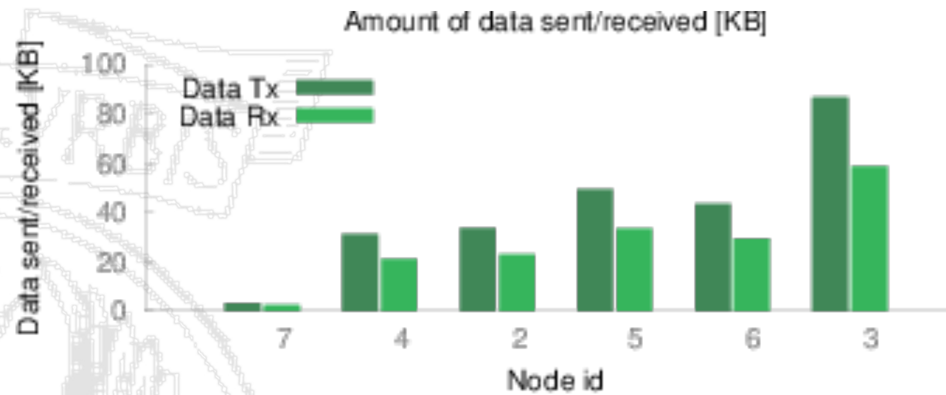
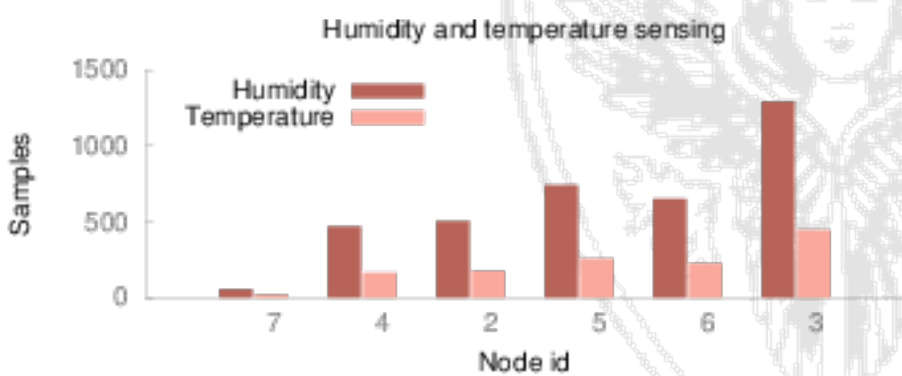
Feasibility study



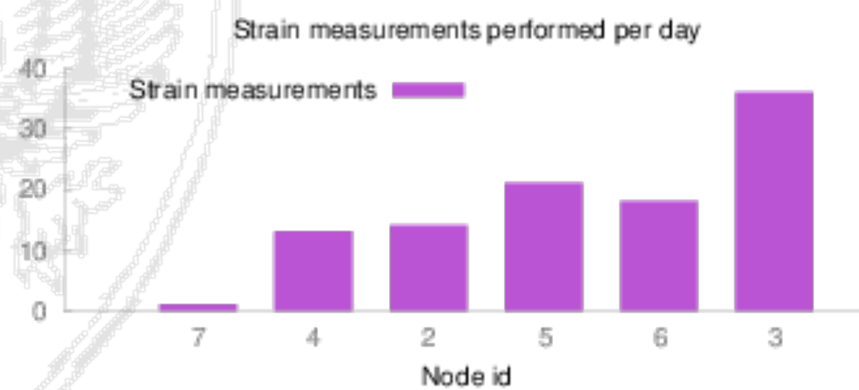
Up to 133 mJ harvested per train passage



Transmit/receive tens of KB



Collect hundreds of humidity and temperature samples

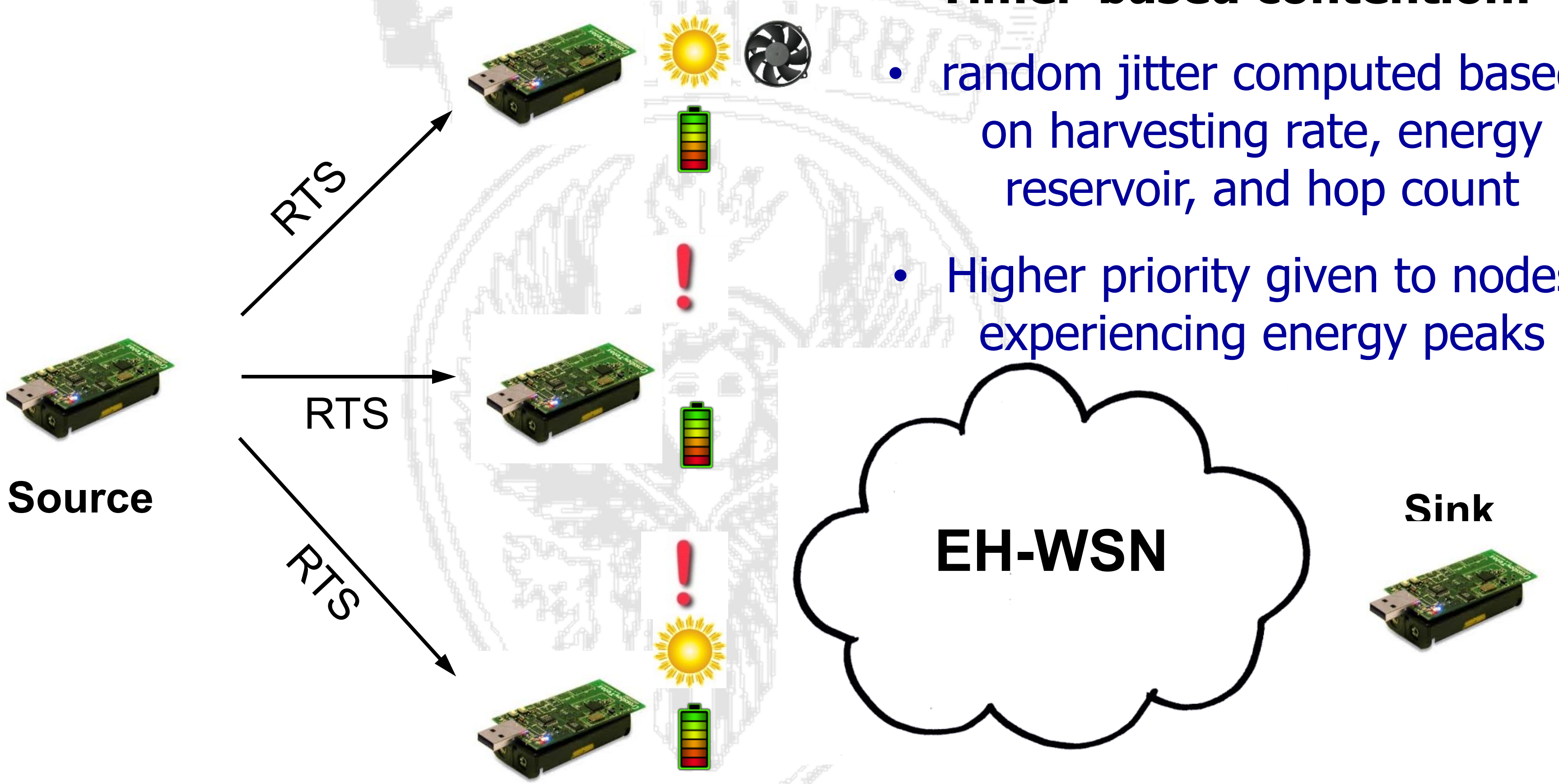


Up to 36 strain measurements per day

Harvesting-aware routing

Timer-based contention:

- random jitter computed based on harvesting rate, energy reservoir, and hop count
- Higher priority given to nodes experiencing energy peaks



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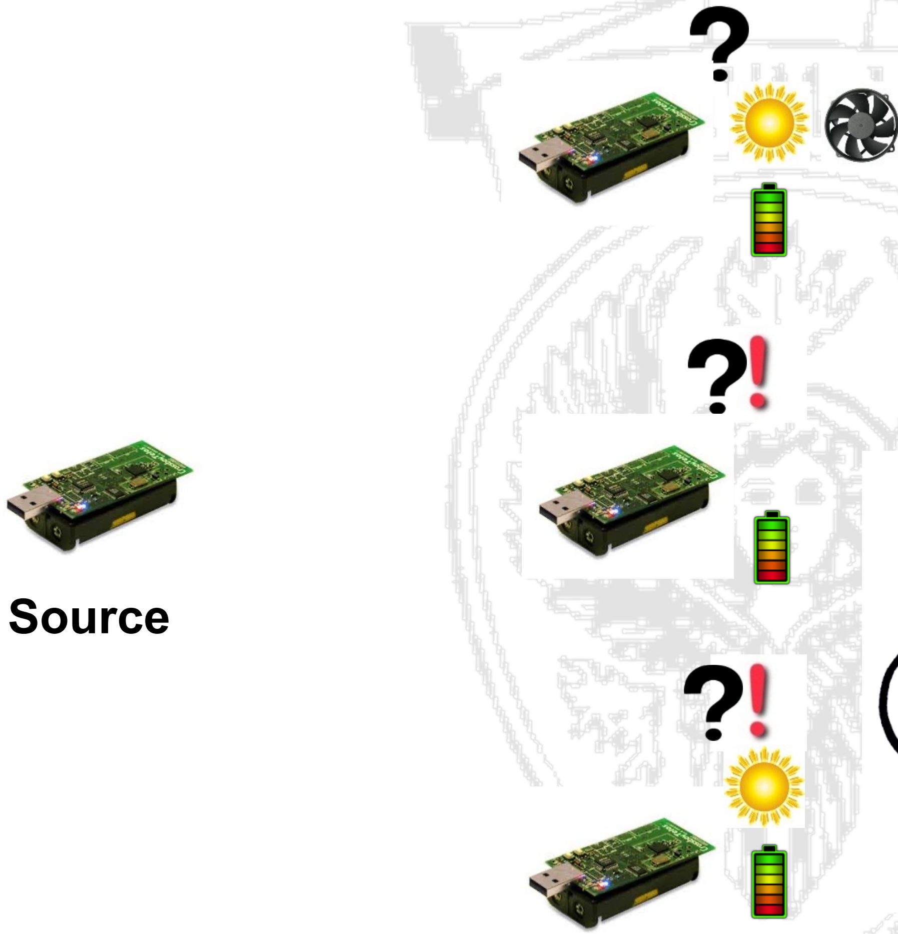
Harvesting-aware routing



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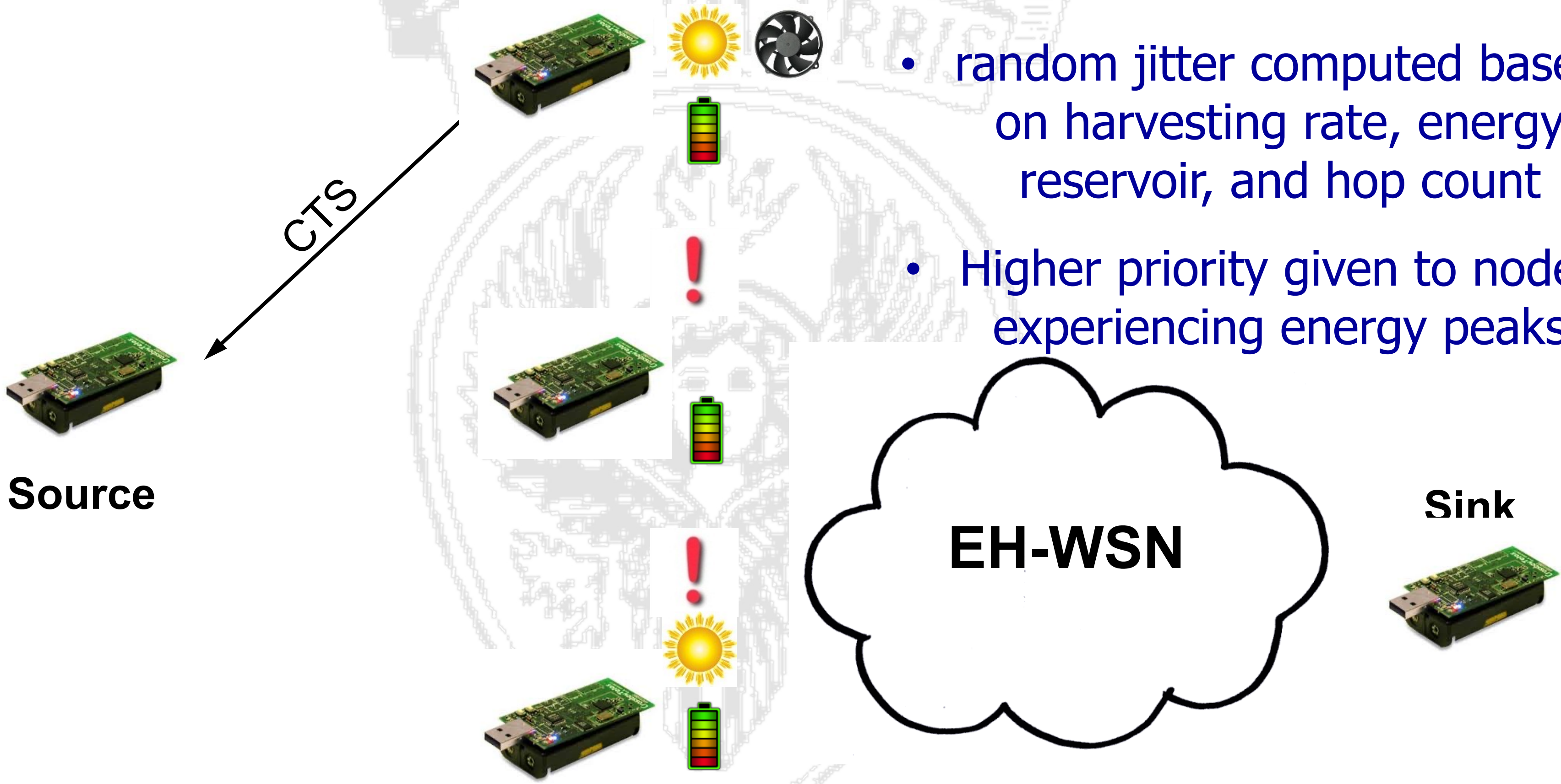

Harvesting-aware routing

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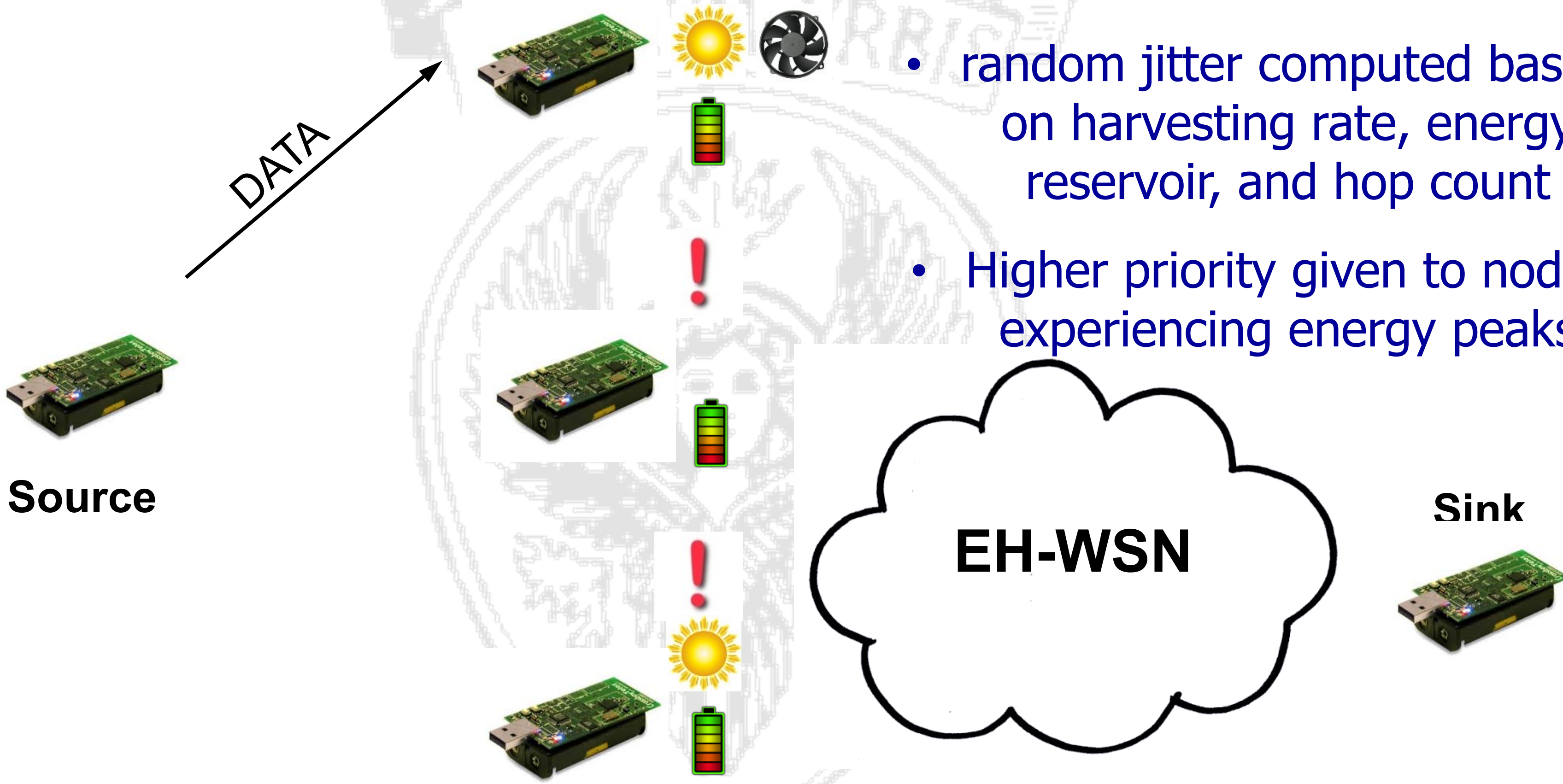

Harvesting-aware routing

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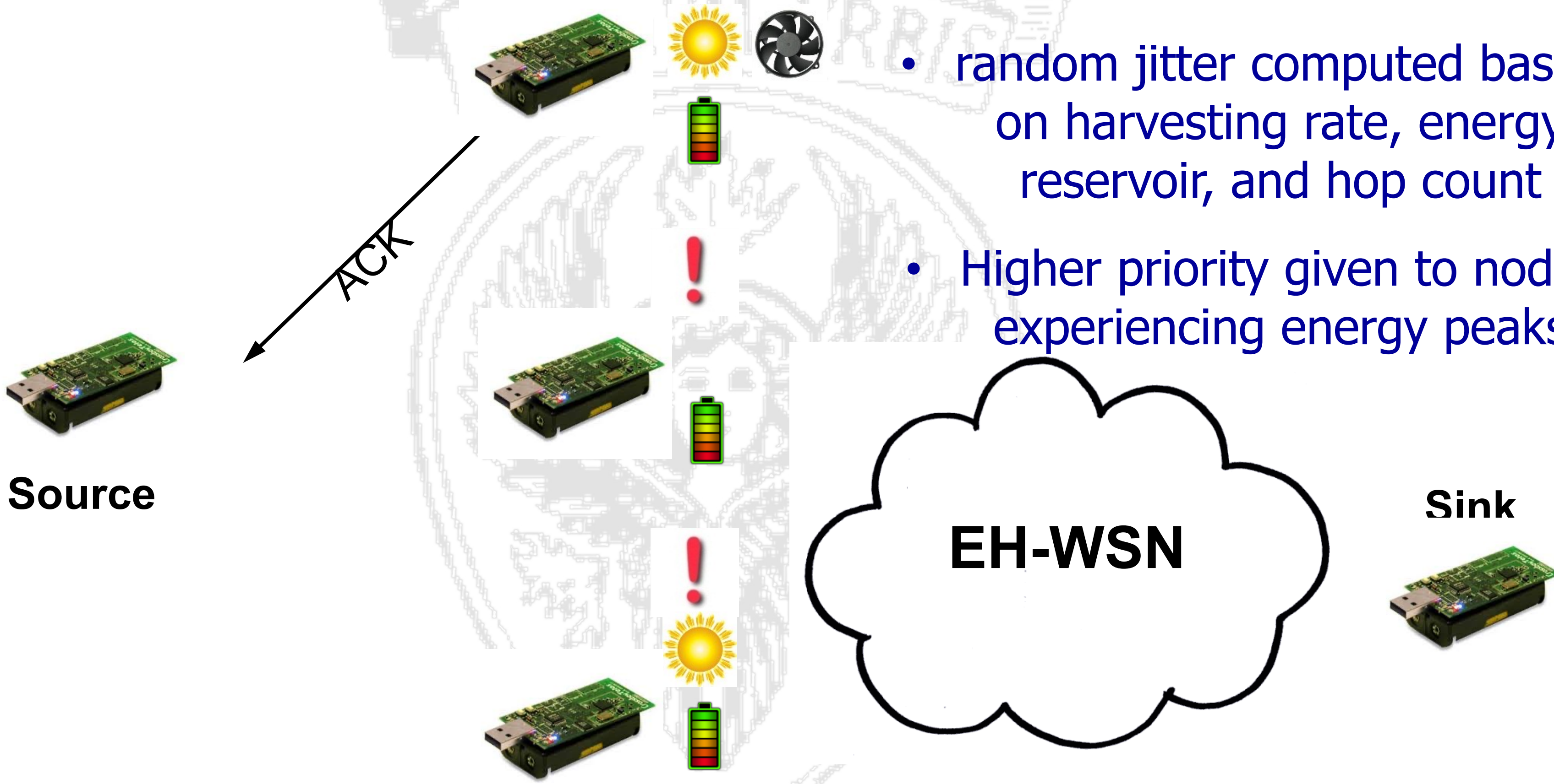
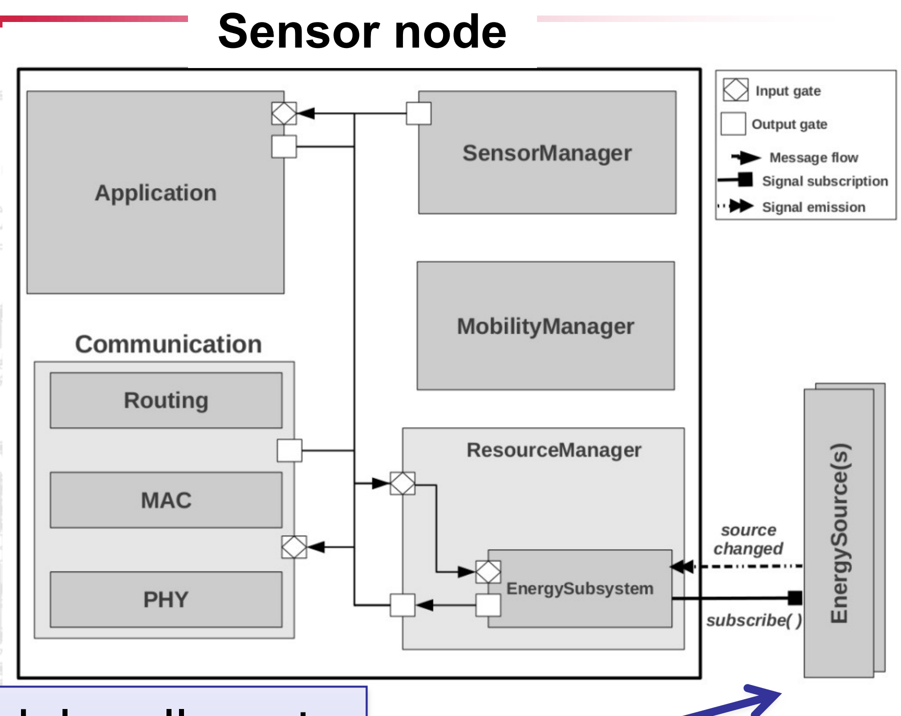


GreenCastalia: Motivation

- **GreenCastalia features**
  - Support for multi-source harvesting
  - Support for multi-storage devices
  - Support for energy predictions
  - Easily customizable
  - Based on Castalia / OMNET++



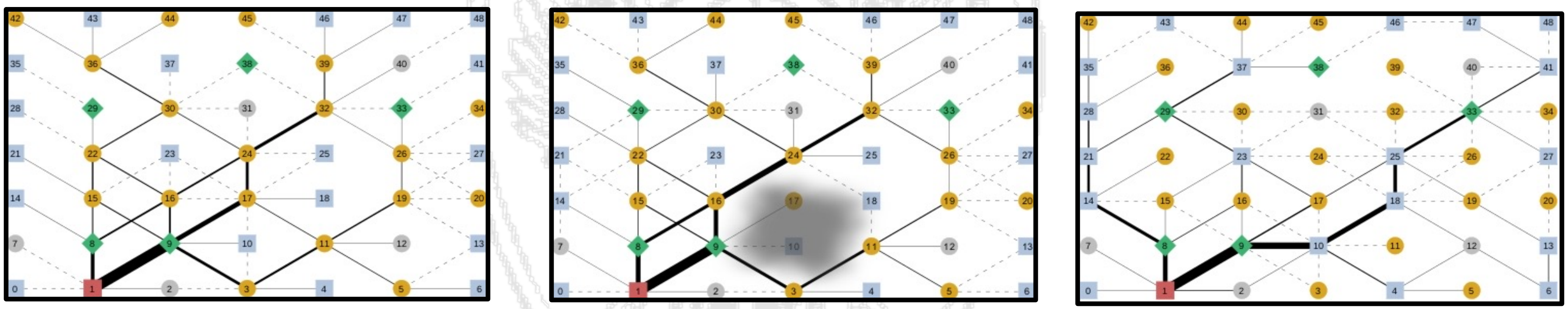
TraceEnergySource module: allows to feed the simulator with timestamped power traces collected through real-life deployments, or with energy availability traces obtained by data repositories or meteorological stations

Harvesting-aware routing: Results

Simulation settings

- 120x120 meters field (7x7 grid deployment)
- Nodes with heterogeneus energy harvesting capabilities:
  - solar, wind both, none

11am | **5pm with shadow zone** | **8pm**

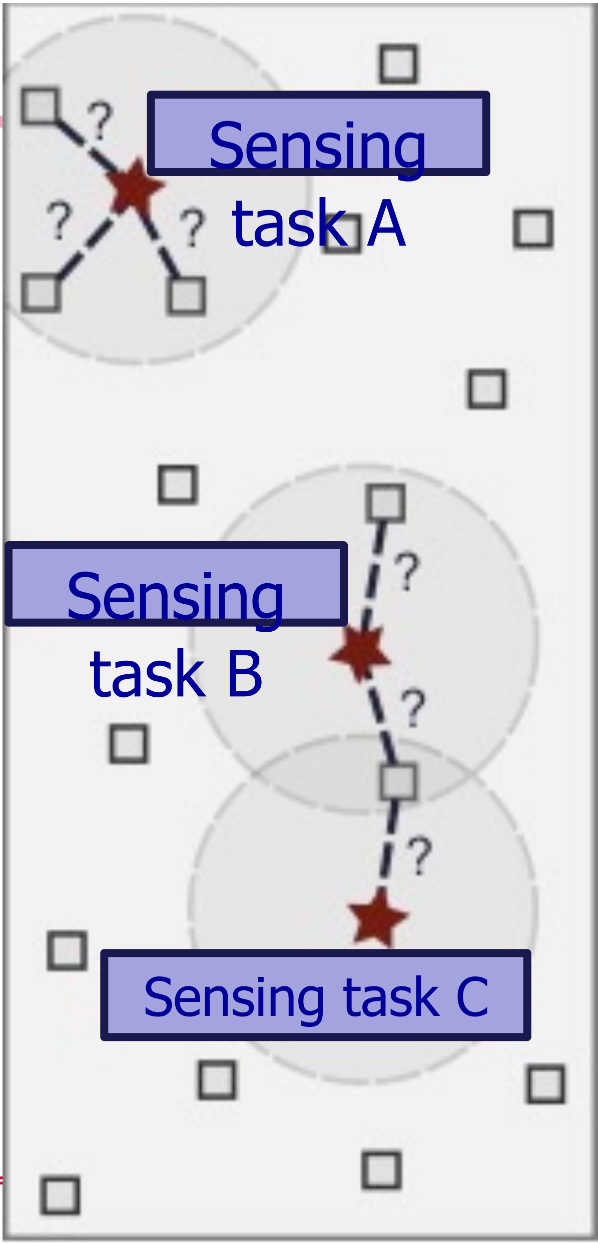


Self-adaptive behaviour: nodes experiencing energy peaks are selected with higher priority as next hop relays

Task allocation

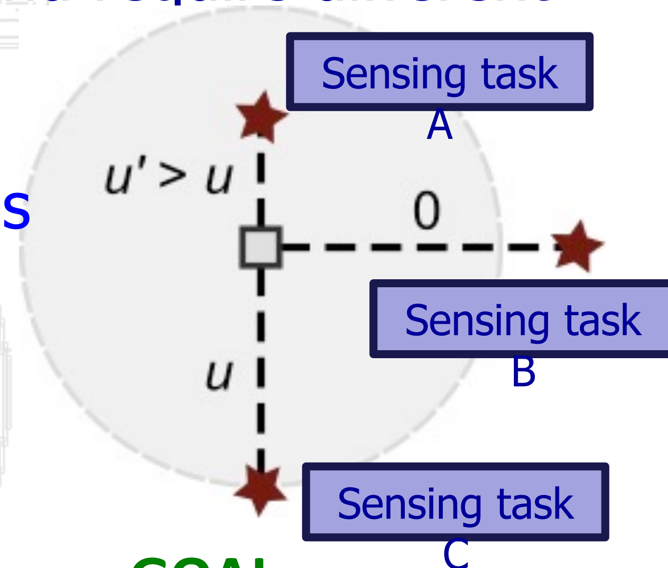
- Sensing tasks (missions) arrive in the network dynamically over time at different locations
- Multiple missions active at the same time, competing for the sensing resources of the network

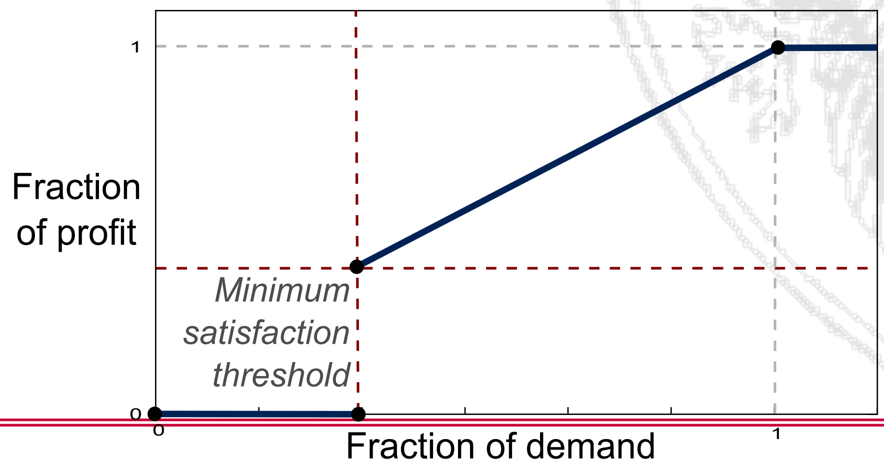
Decide which sensor(s) should be assigned to each mission



QoS-aware operations

- Missions have different priority (profit) and require different amount of resources (demand)
- **Assigments are not all equal..**
  - Nodes contribute to different missions with different **utility (quality of information)**
  - Achieved profit depends on allocated demand





GOAL

Maximize the profit obtained by the network for missions execution within a given **target lifetime**

EN-MASSE

- Distributed heuristic for task allocation in WSN with **energy harvesting**
- Nodes make independent decisions about task execution
- Decision based on:

Partial profit

1. Profit of the mission
2. Potential contribution to the mission

Tune eagerness

1. Target network lifetime

Classify missions

1. Current energy level of the node (fuel cell + supercap)
2. Energetic cost of the mission
3. Future energy availability

Mission classification

A new mission arrives → check energy requirements and energy availability

More willing to accept ↓

Fuel cell/battery required not enough energy in the supercapacitor to execute the mission; use energy from the fuel-cell

Capacitor sustainable mission energy cost sustained by supercapacitor

Recoverable mission energy cost sustained by supercapacitor AND energy cost recovered through harvesting before the next mission arrives

Free mission energy cost expected to be fully sustained by energy harvesting

Mission classification

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Recoverable mission energy cost sustained by supercapacitor AND energy cost recovered through harvesting before the next mission arrives

Free mission energy cost expected to be fully sustained by energy ha

REQUIRE ENERGY PREDICTIONS

Mission selection rule

capacitor sustainable and recoverable

- Expected partial profit of a mission

$$\overline{p} = \frac{E[u]}{E[d]} \times \frac{E[p]}{P},$$

Always for free missions

P maximum achievable profit: E[u],E[d],E[p] expected utility, demand and profit of a given mission

- Partial profit achievable by a node participating to a mission

$$p^* = \frac{e_{ij}}{d_j} \times \frac{p_j}{P} \times w$$

w weight which depends on mission classification. Bid if p*>=expected partial profit

Task-Allocation EN-MASSE-In summary

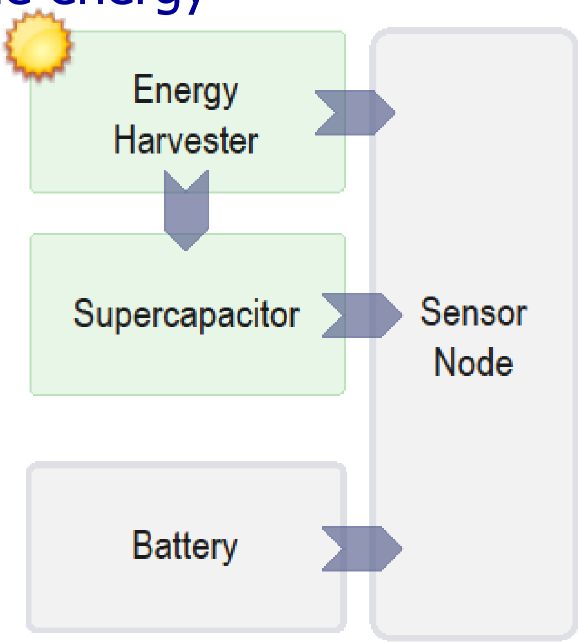
A **decentralized** harvesting-aware heuristic

Key features:

- Uses short and long term energy predictions for pro-active energy allocation
- Takes into account missions arrival statistics to make sustainable allocation decisions
- Considers the impact of executing a mission on node energy

Higher priority to less-impacting missions

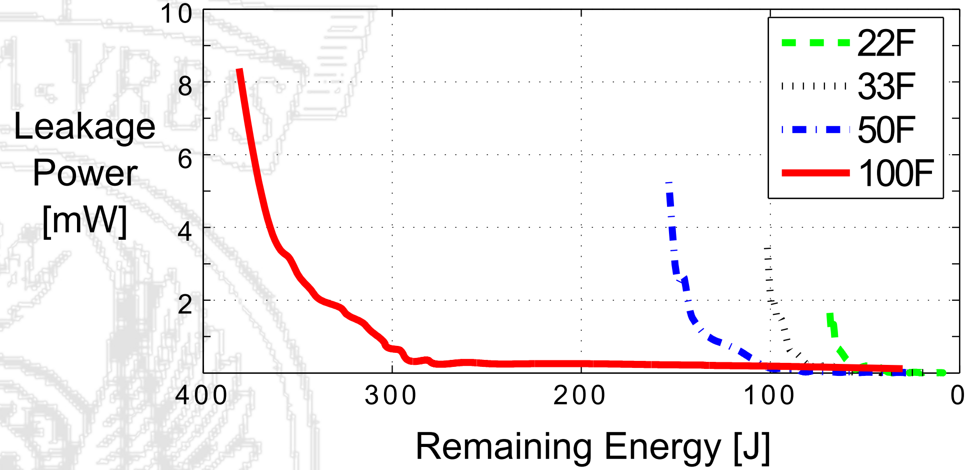
1. **Free:** fully sustained by harvesting
2. **Recoverable:** sustained by supercapacitor and recovered before next mission
3. **Capacitor-sustainable:** sustained by supercapacitor
4. **Battery-required:** sustained by battery



Modeling real harvesting systems

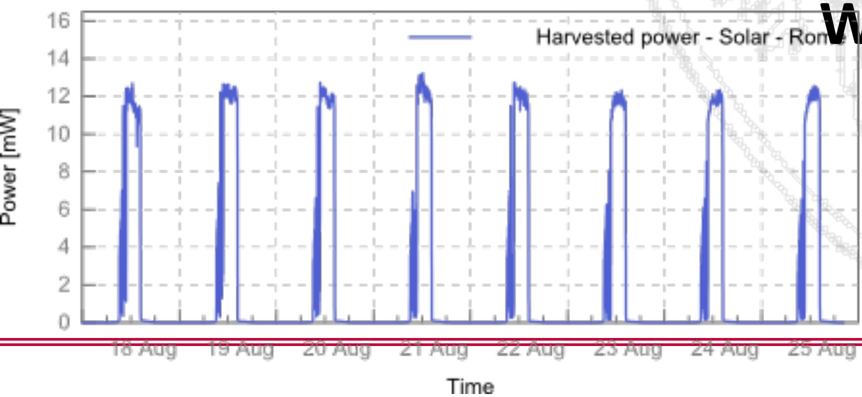
Non-ideal supercapacitors

1. Finite size
2. Charging\discharging efficiency < 1
3. Leakage\self-discharge

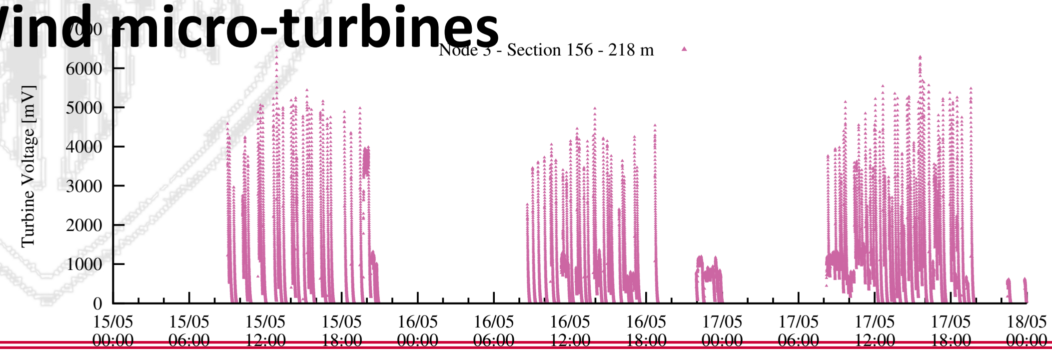


Real-life energy traces

Photovoltaic cells



Wind micro-turbines



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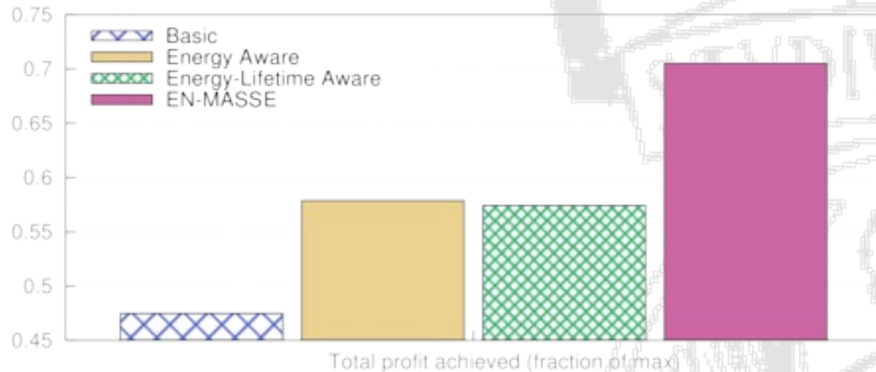
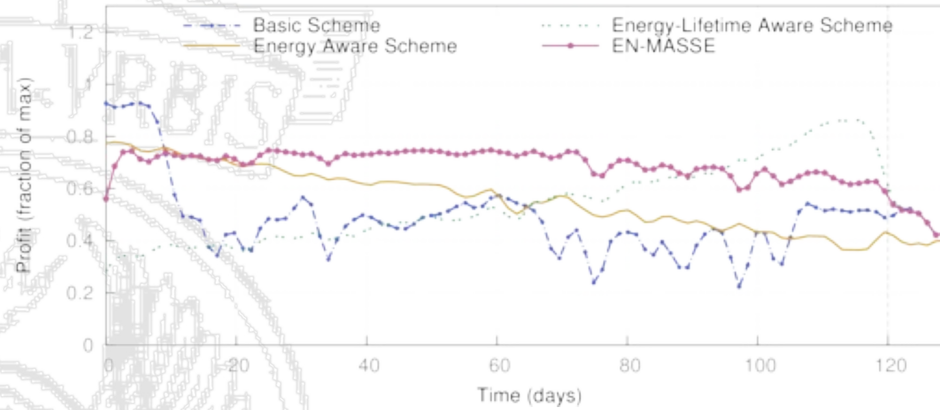
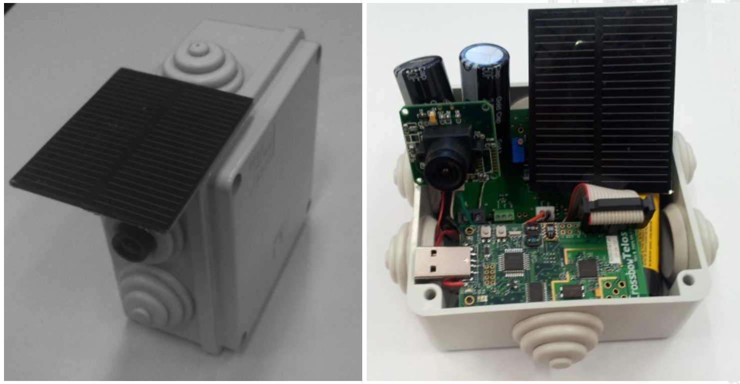
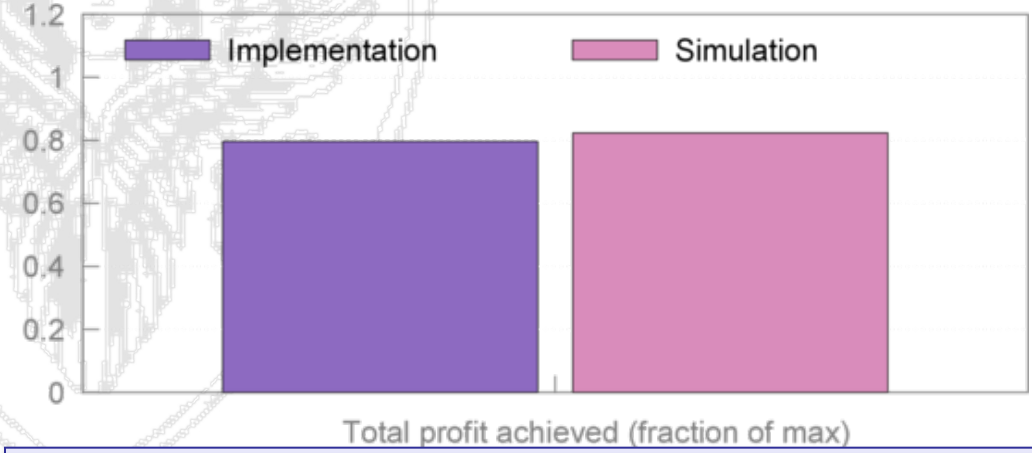
Performance evaluation





Profit: up to 60% higher than SoA **Stable profit: 70-80% of maximum**





In-field testbed validation

Gap between simulations and testbed: **less than 3%** of maximum profit

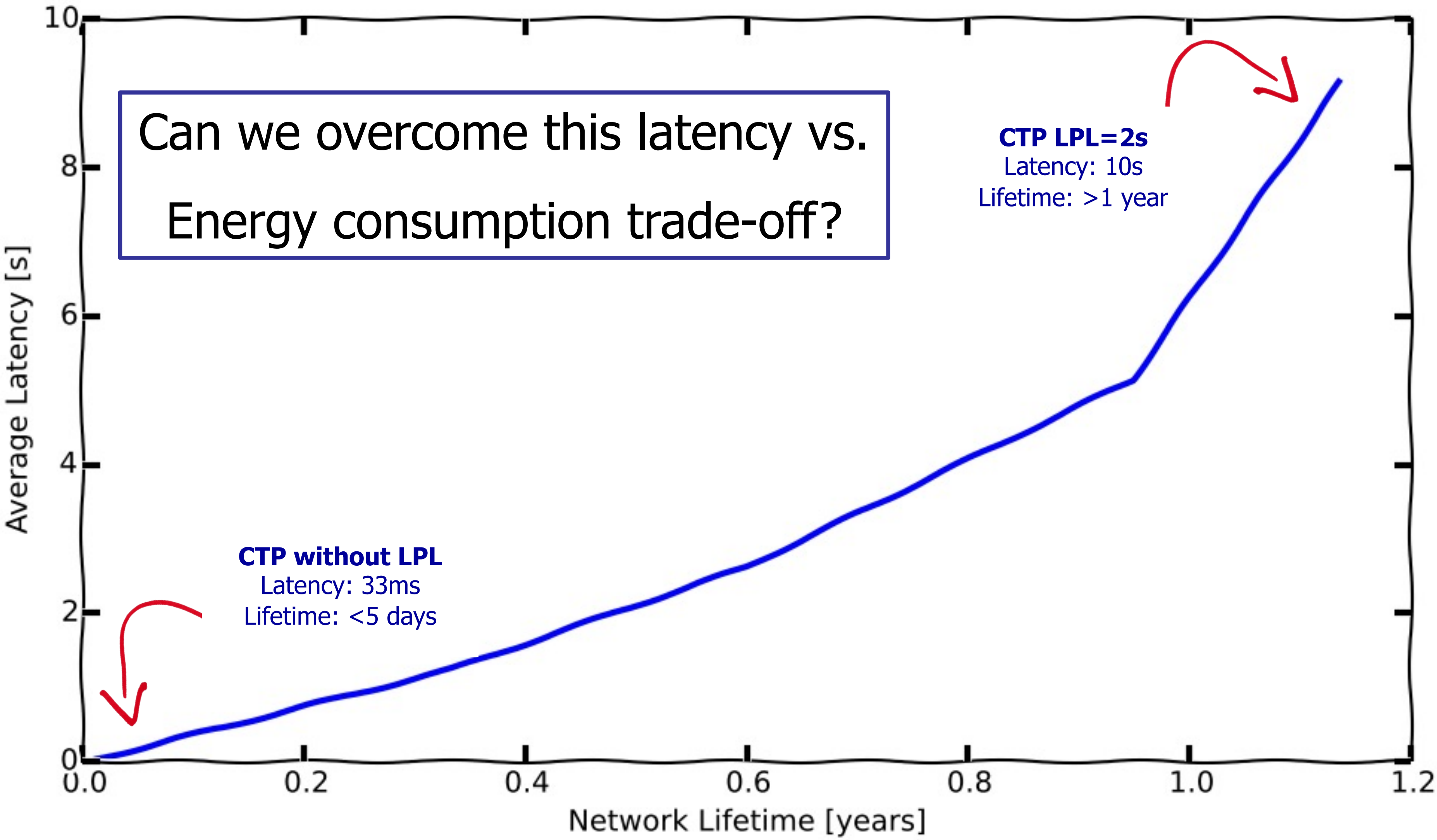
Protocols for wake-up radio enabled Internet of Things, a.a. 2020/2021

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

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

Latency vs. Energy Trade-off



A new approach: Wake-up radios

- Enable **on-demand** communication
  - Low-power dedicated hardware, continuously monitoring the channel
  - Nodes keep their main radio OFF unless data communication is needed
  - Virtually eliminates idle listening on the main radio
  - Based on the architecture, possibility to selectively wake-up only specific nodes
- Terrific energy saving especially in event-based applications
- No latency vs. energy trade off

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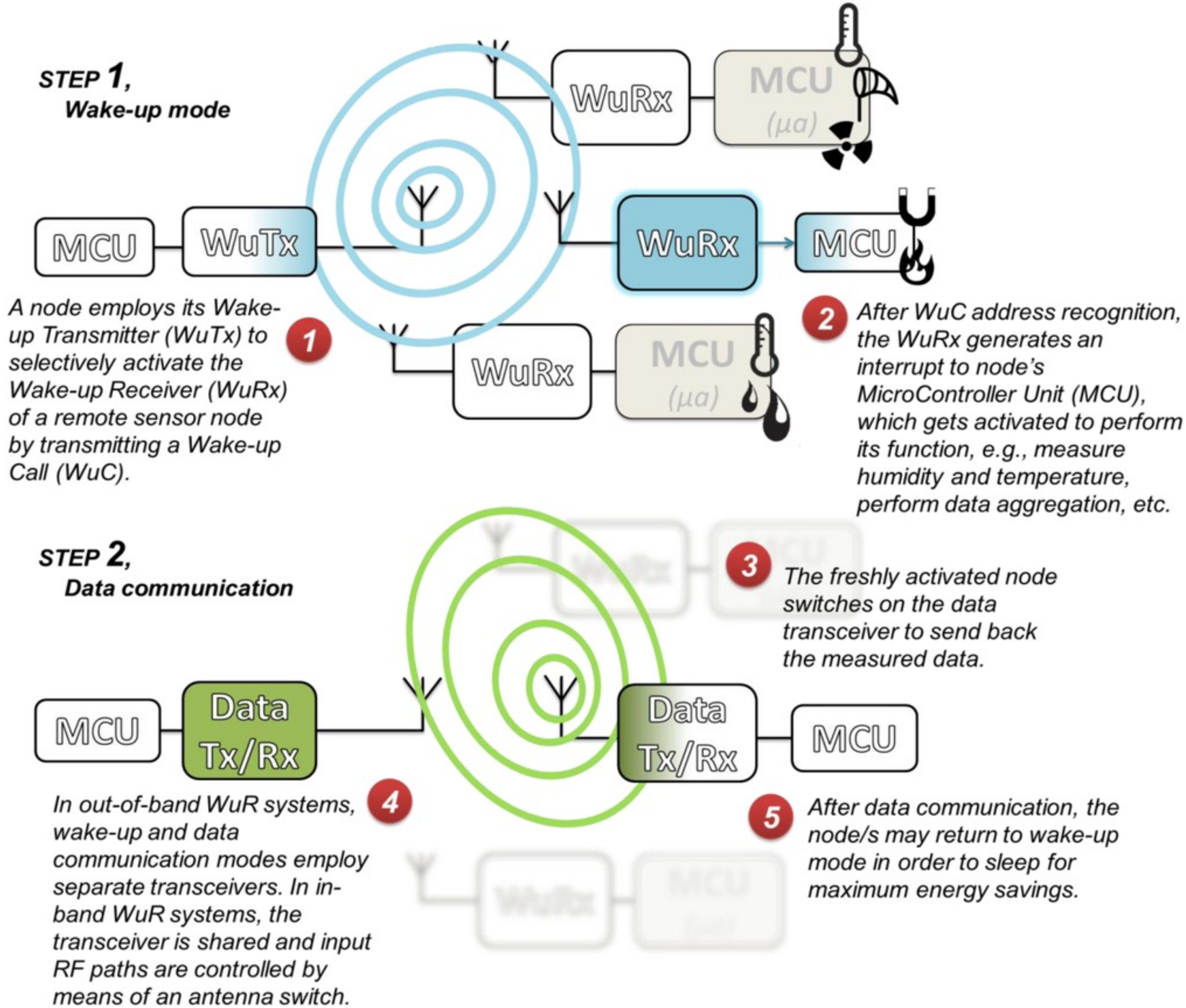
WRx-based communication



State of the art

Passive WURs

- Harvest power from the radio signal
- No external power supply
- Low sensitivity = short wake-up range (3 m)
- Prone to interferences

RFID-based

- Shifts energy toll to the transmitter
- Unsuitable for P2P networking

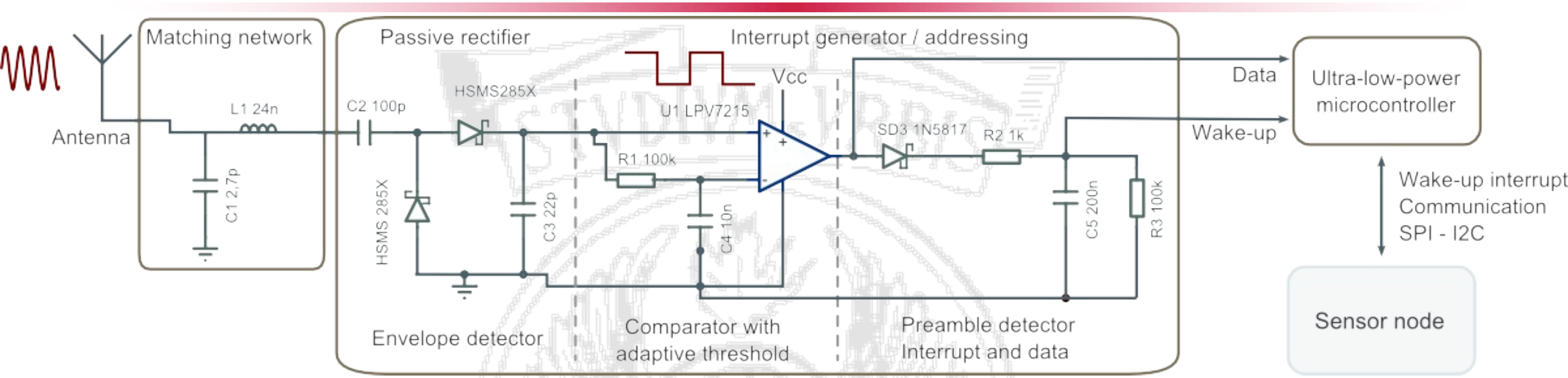
Semi-active WURs

- External power is needed
- Higher sensitivity = longer wake-up range
- Sensitivity: -35 to -47 dBm
- Power consumption: 2.3 to 10 uW

Nano-power WURs

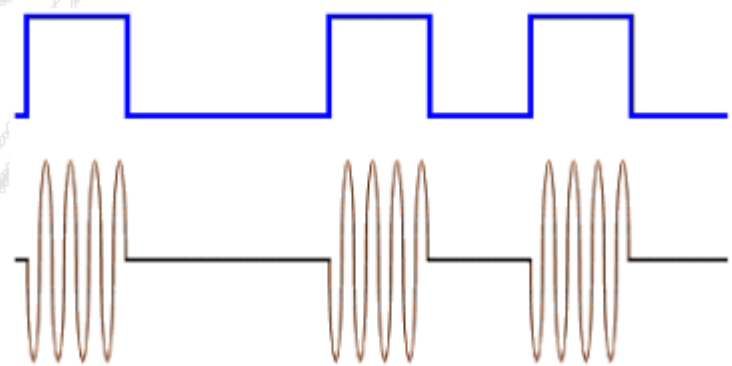
- Power consumption: 98-270 nW
- Wake-up range <= 10m

Our wake-up radio architecture

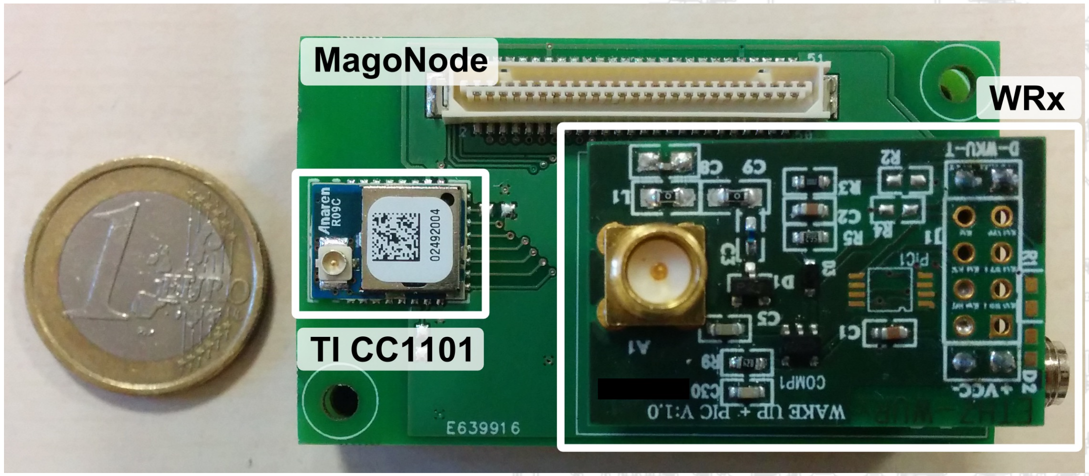


Collaboration with L. Benini and M. Magno, ETHZ

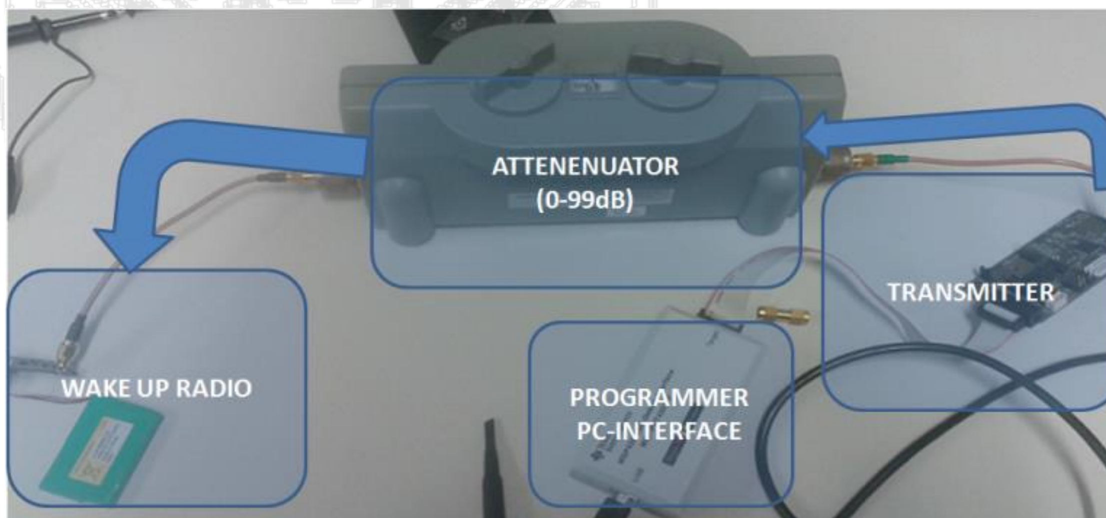
- OOK modulation
- Very low power consumption (< 1.3uW)
- High sensitivity (up to -49dBm)
- Fast reactivity (wake-up time of 130us)
- **Selective addressing**



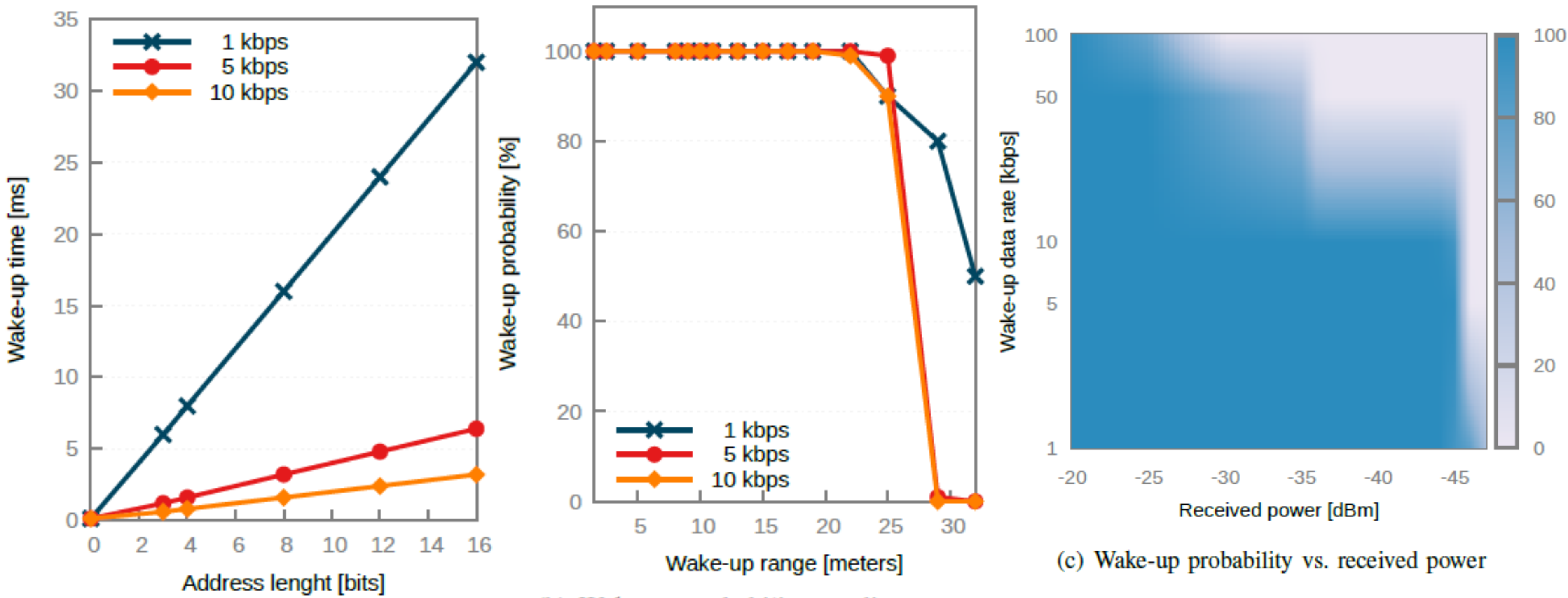
WRx prototyping and testing



- TI CC1101 used to transmit WRx requests
- on-board PIC microcontroller to perform addressing while keeping the MagoNode in deep-sleep



Experimental performance



(a) Wake-up latency

(b) Wake-up probability vs. distance

(c) Wake-up probability vs. received power

- Sensitivity: -49 dBm
- Maximum wake-up range: 42 m (no addressing)
- Wake-up probability depends on WTx data rate and distance

WRx communication protocol

- **Key idea: Semantic wake up addressing**
- use WRx addresses to wake up a node or a group of nodes based on their state
  - selectively wake up only good potential relays
  - e.g., relays ranked based on advance toward the sink, traffic and channel conditions
  - WRx addresses have a semantic meaning
  - each node dynamically changes its own WRx address to reflect its state

Wake up enabled comm. stack

Wake-up-enabled communication stack

- Exploits proposed WuR to addresses latency vs. energy consumption tradeoff
- Both interest dissemination and convergecasting primitives
- Key idea: use wake-up addresses to wake up a node or a group of nodes based on certain properties

Interest dissemination

- Transmission of commands from sink to nodes
- Goal: avoid reception of duplicated packets
- Use current wake-up address to indicate whether a packet was already received

FLOOD-WUP

- Nodes are assigned shared wake-up broadcast addresses: w_a and w_b
- Initially in sleep, wake-up radio active with address $= w_a$
- Sink broadcasts first interest packet preceding it with wake-up sequence w_a
- Nodes with address w_a wakes up, sets main radio to RX, receive packet
- Then change broadcast wake-up address to w_b
- After a random time, nodes re-broadcast packet preceding it with w_a
- No duplicates, only nodes with address w_a wake up

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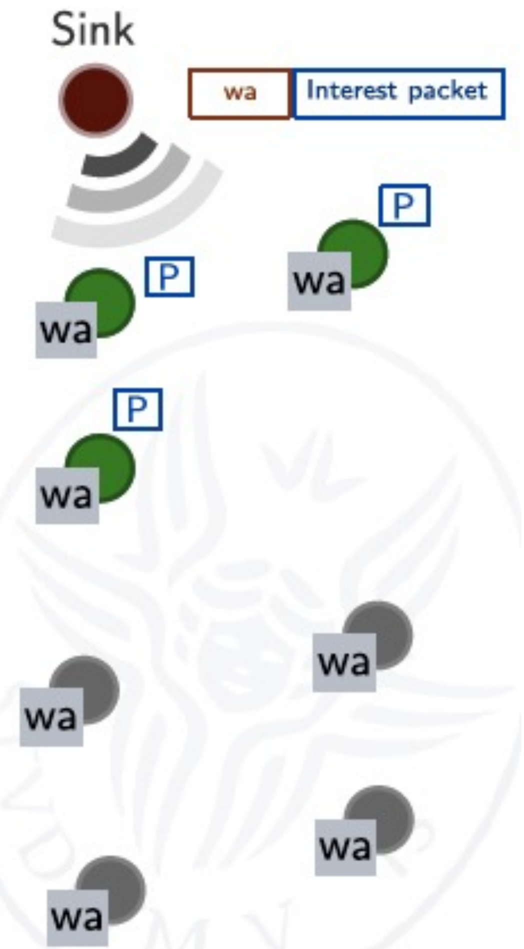

FLOOD-WUP

- Nodes are assigned shared wake-up broadcast addresses: w_a and w_b
- Initially in sleep, wake-up radio active with address $= w_a$
- Sink broadcasts first interest packet preceding it with wake-up sequence w_a
- Nodes with address w_a wakes up, sets main radio to RX, receive packet
- Then change broadcast wake-up address to w_b
- After a random time, nodes re-broadcast packet preceding it with w_a
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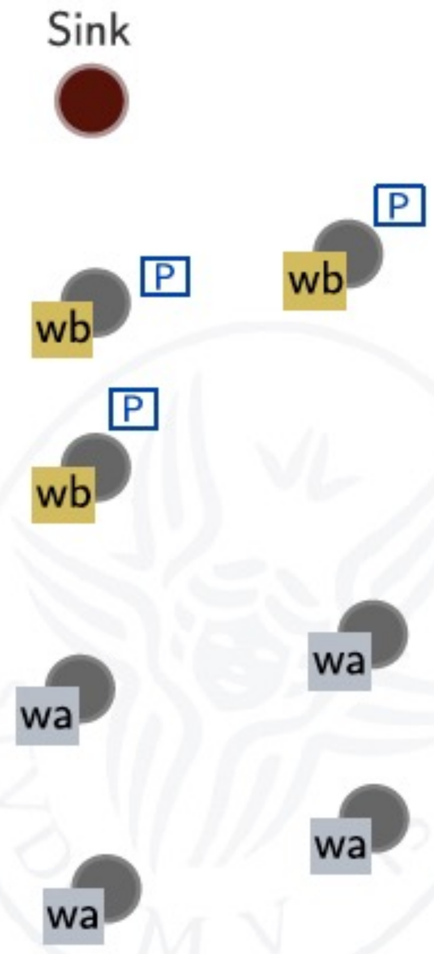

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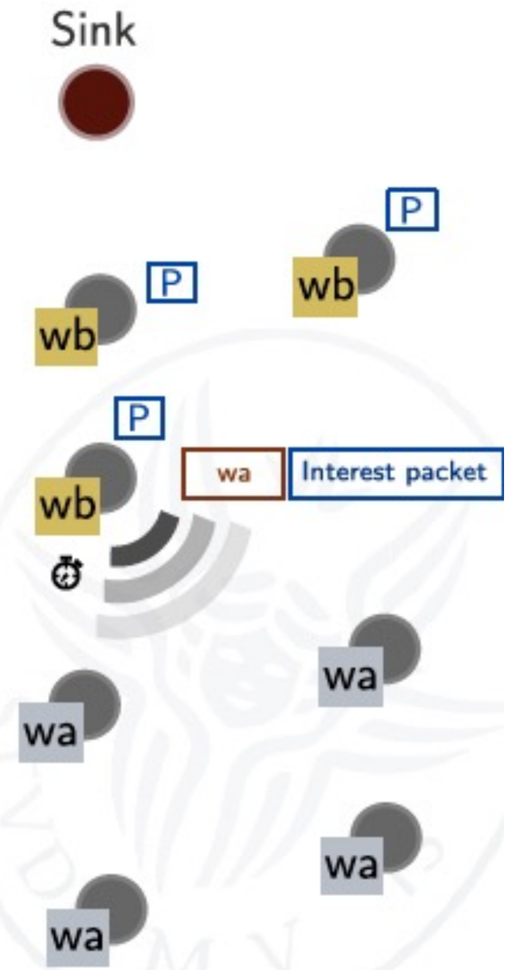

Flood-WUP

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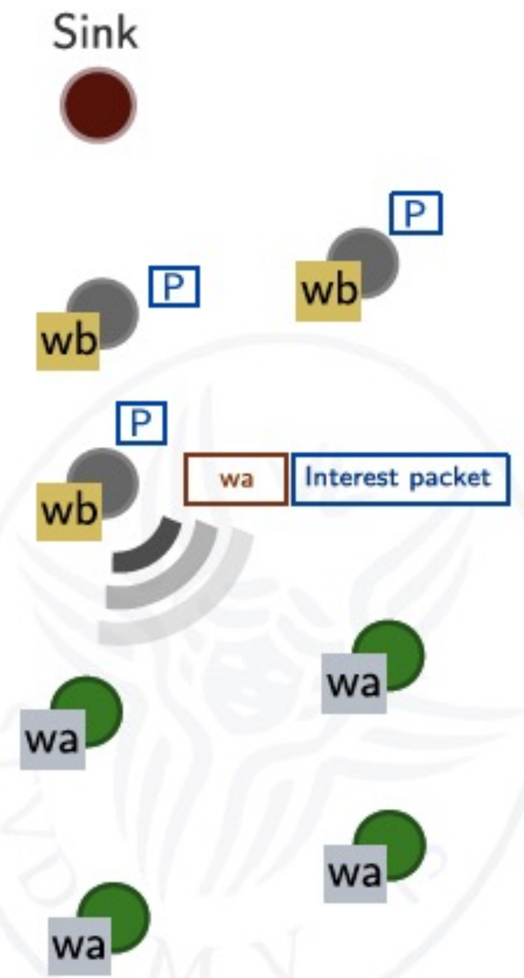


Converge Casting: GREEN-WUP

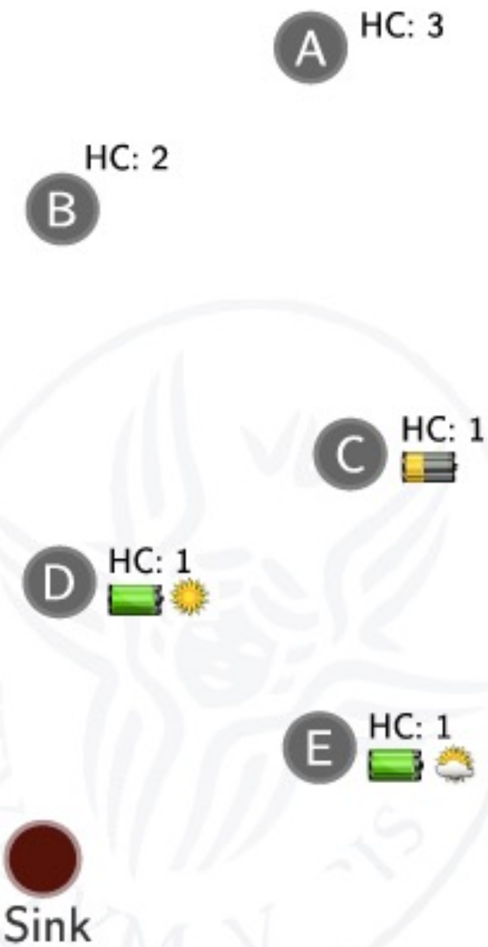
- Multi-hop data transfer to sink
- Energy harvesting scenario: nodes scavenge power from environment
- **Key idea**: Selectively wake-up only **good** potential relays
- Ranked based on hop count, residual energy, energy intake (harvesting-aware)
- Wake-up addresses have a **semantic meaning**
- Nodes dynamically change their wake-up addresses over time to reflect their state
  - Format | Hop count | Energy class |
  - Energy class depends on harvesting and residual energy

GREEN-WUP

- Example: energy classes

  max battery level > threshold T_{high} and excess energy from harvesting
  2 battery level > T_{high}
  1 T_{low} < battery level ≤ T_{high}
  0 battery level ≤ T_{low}

- Node B has a packet to transmit
- Sends RTS only to nodes with hopcount = 1 and energy = max. Then it goes to sleep
- Only node D wakes up. Other nodes continues to sleep
- Iterate on energy class if no relay found
- CTS, DATA, ACK..



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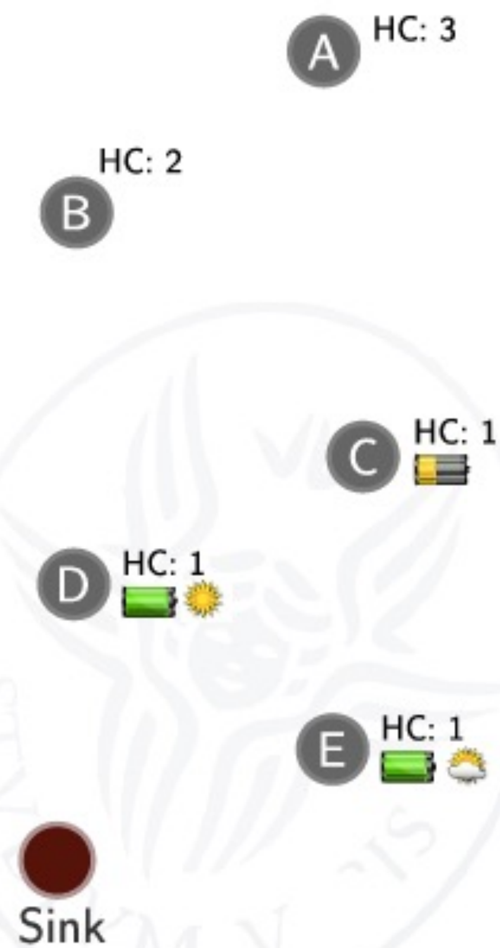

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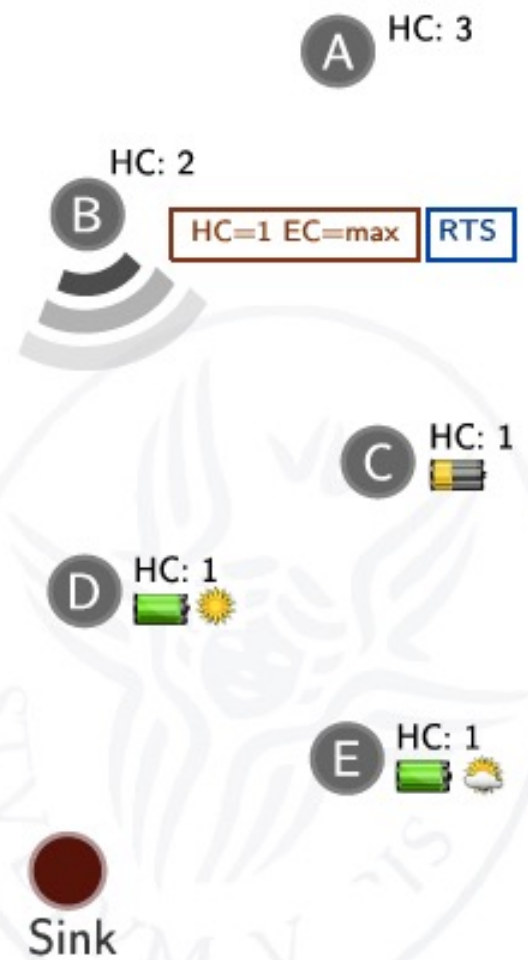

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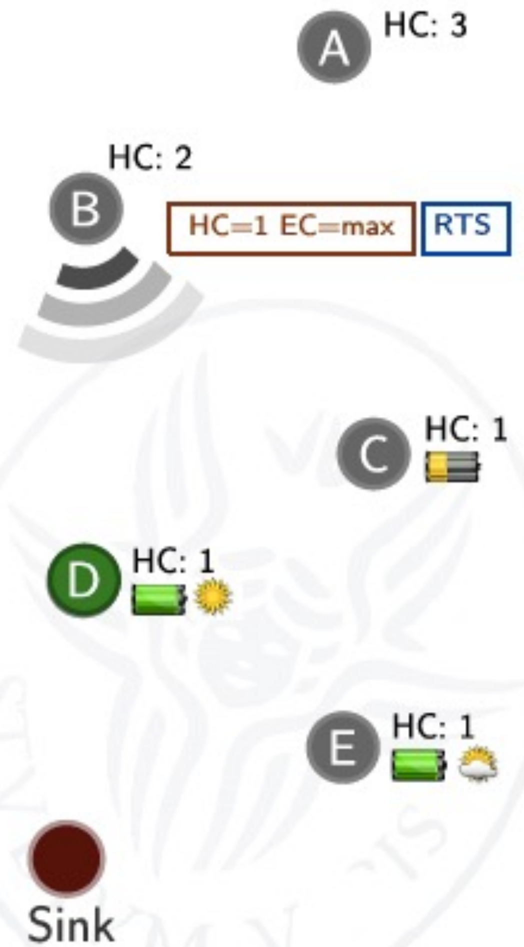

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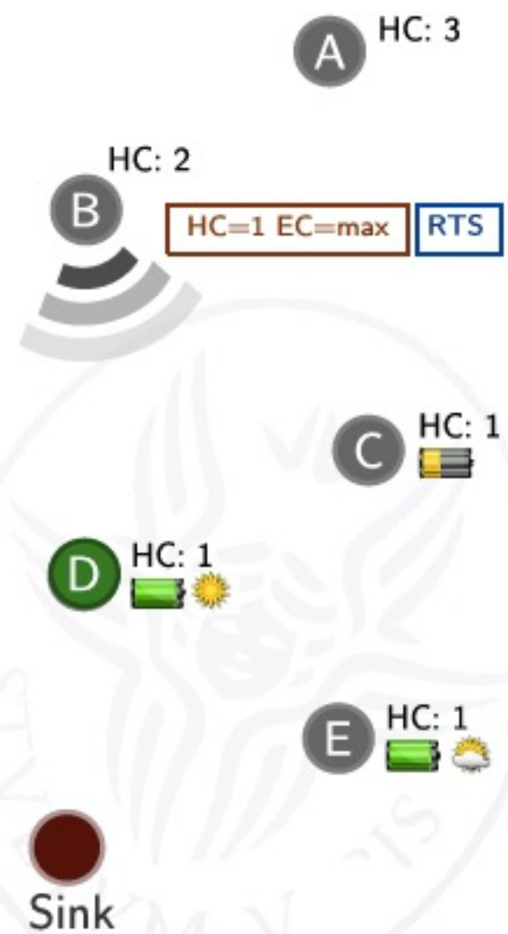

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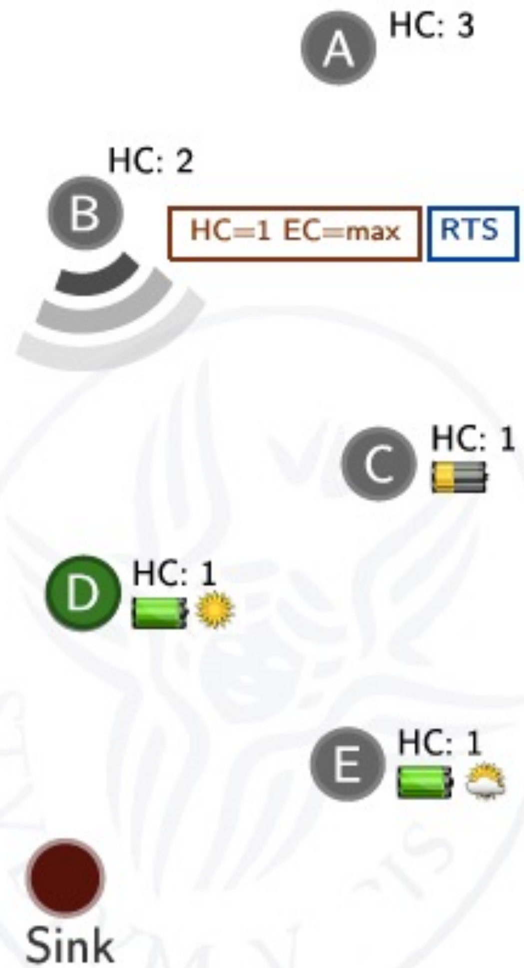


SAPIENZA
UNIVERSITÀ DI ROMA

Sim. scenario

Different concept of wake up radio

- Active, higher energy consumption

+ Semantic WUP radio addresses

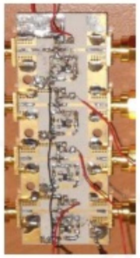
+ Only one transceiver (TX)

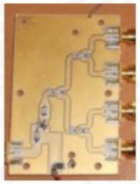
Key feature of the proposed WuR

- Selective addressing of nodes combining frequency-domain and time-domain addressing space
- **Wake-up signal**: sequence of continuous-wave pulses OOK modulated over c IEEE 802.15.4 channels (2.4 GHz ISM band)

Prototyping and design validation

- Prototype with 4 channels at 2410, 2435, 2455 and 2480 MHz
- Lab experiments: sensitivity of -83 dBm
- In-field experiments: RX node (TelosB + WuR), TX node (MTM-CM3300)
- Varying distance up to 120 m
- TX node sends 4 different wake-up sequences (8 symbols) 100 times
- Wake-up statistics recorded by RX node
- False positive and false negative both $< 1\%$
- Simulation for power consumption scaling: 168 μW per filter, 1.6 mW overall (including LNA)

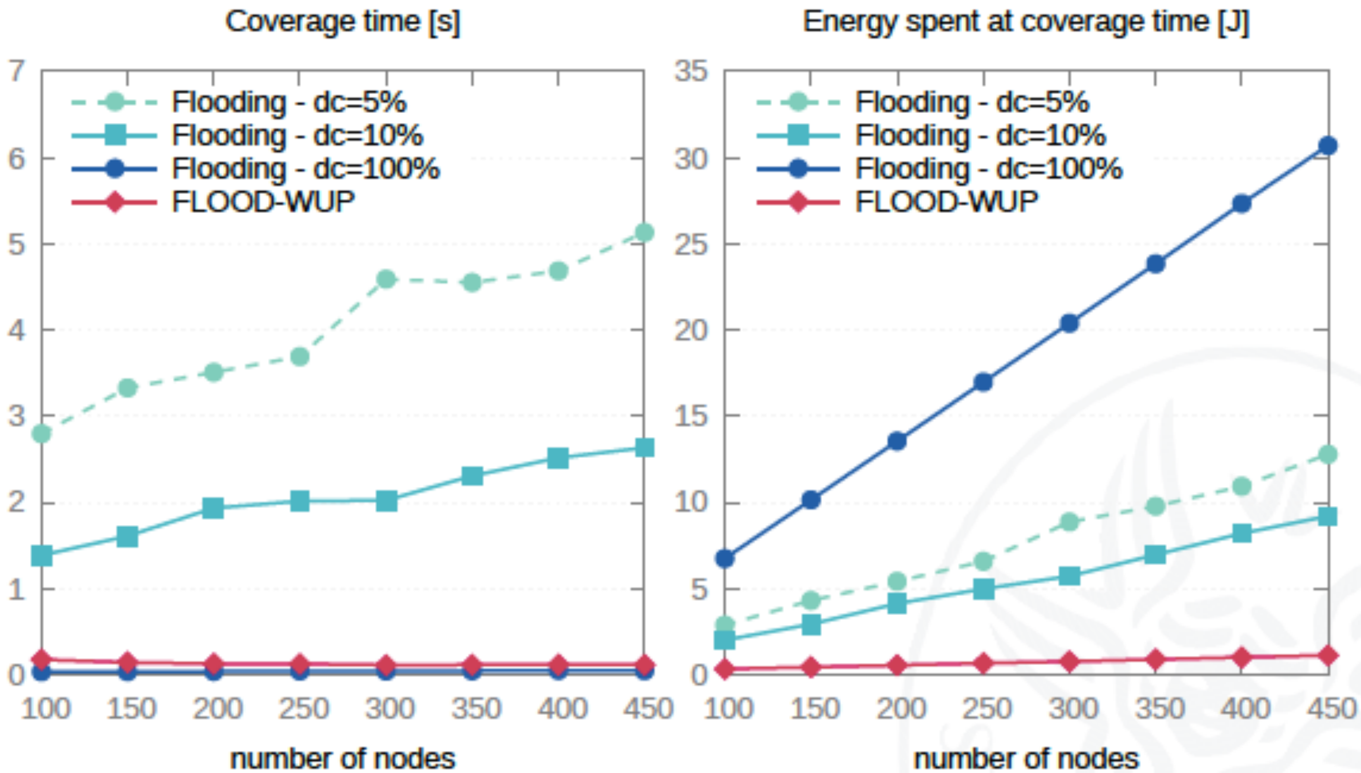




Green Castalia simulations

Chiara Petrioli, Dora Spenza, Pasquale Tommasino, Alessandro Trifiletti
A Novel Wake-Up Receiver with Addressing Capability for Wireless Sensor Nodes. IEEE DCOSS 2014: 18-25

FLOOD-WUP, 100-450 nodes

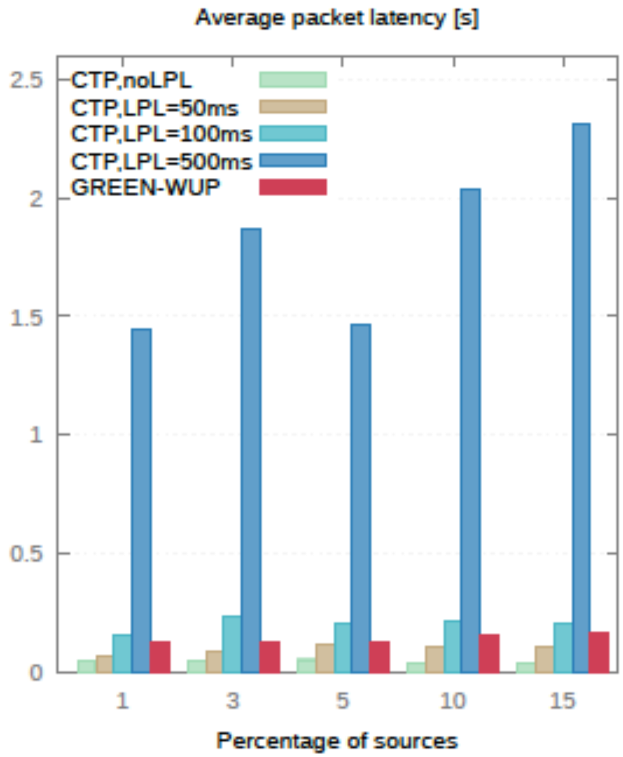


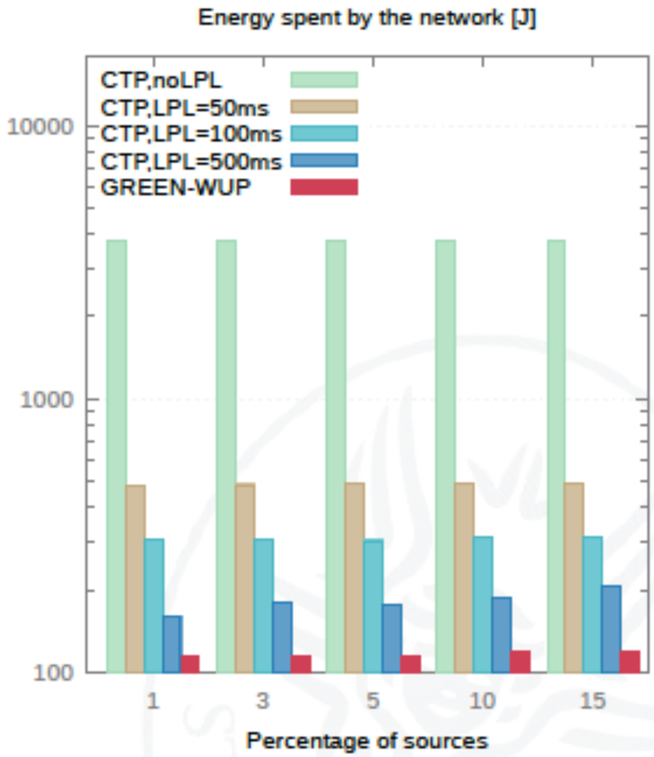
Coverage time similar to Flooding with 100% DC

Energy consumption reduced of up to ≈ 96%

vs Flooding10%: -24x coverage time, -8x energy

GREEN-WUP, network of 100 nodes



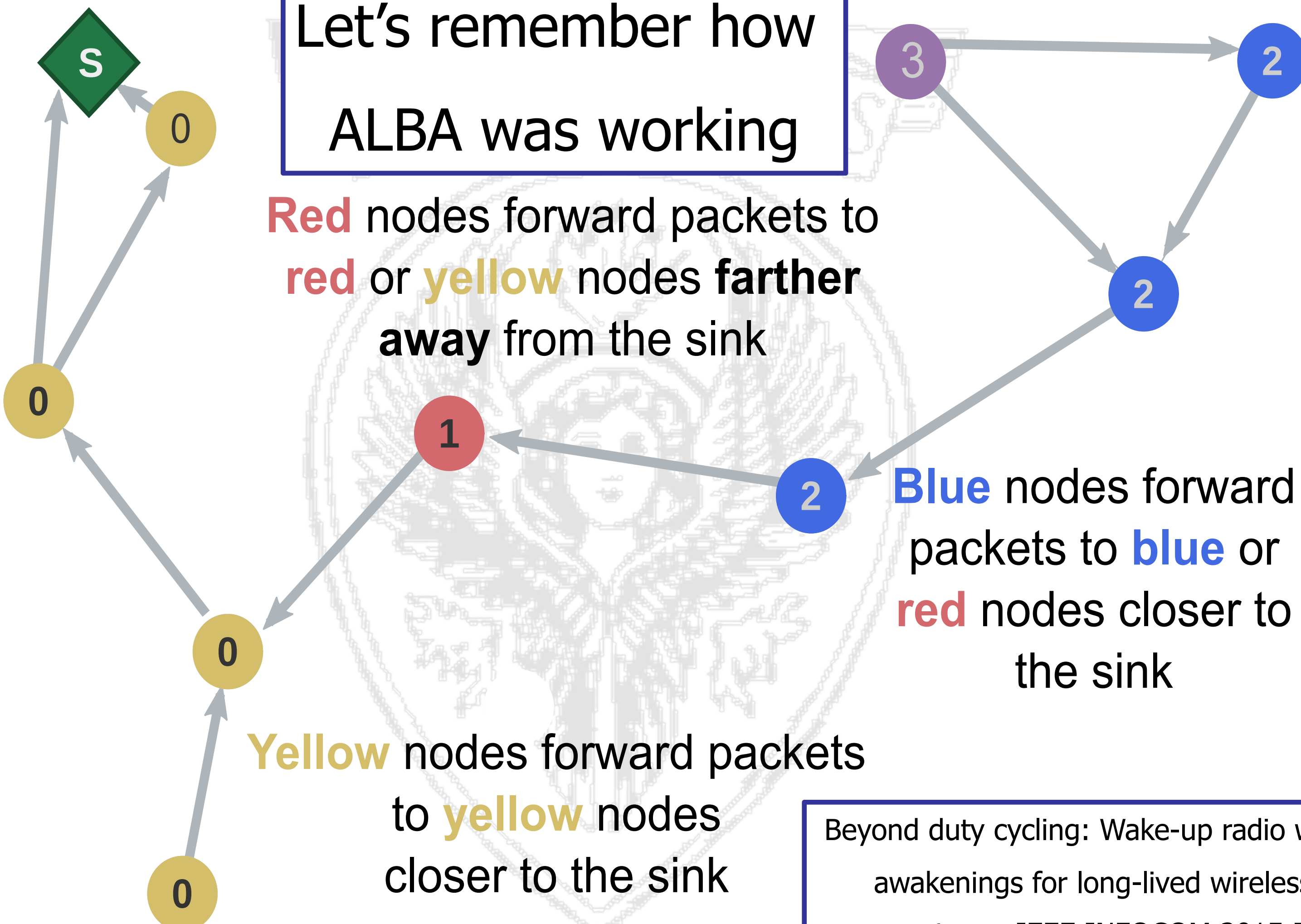


Average latency 100 ms higher than CTP without LPL

Energy consumption reduced of up to $\approx 33x$!

vs CTP+LPL=500ms: latency -16x, -45% energy

Let's remember how ALBA was working



Red nodes forward packets to **red** or **yellow** nodes **farther away** from the sink

Blue nodes forward packets to **blue** or **red** nodes closer to the sink

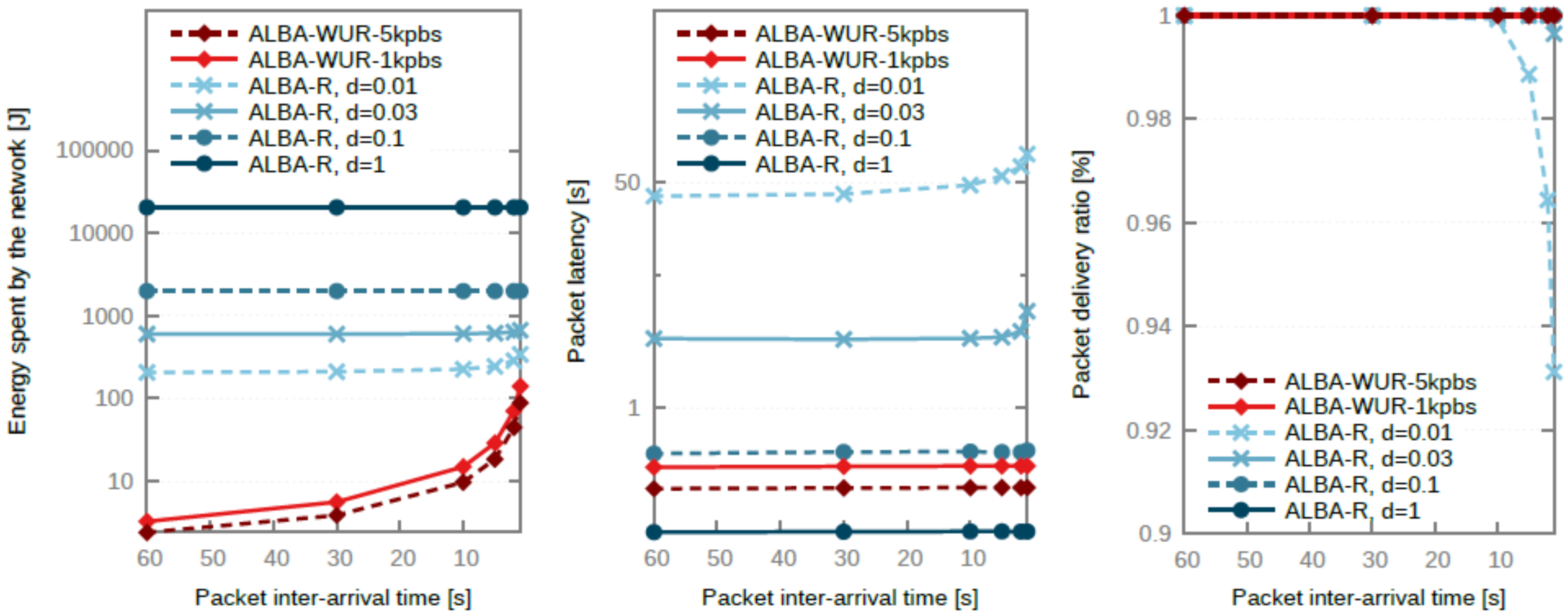
Yellow nodes forward packets to **yellow** nodes closer to the sink

Beyond duty cycling: Wake-up radio with selective awakenings for long-lived wireless sensing systems. IEEE INFOCOM 2015 522-530

Simulation setup

- Comparative performance evaluation:
    a. ALBA-WUR, WRx sequences sent @ 1 kbps, 5 kpbs
    b. ALBA-R with duty d={1, 0.1, 0.03, 0.01}
- Simulation framework: GreenCastalia
- 120 nodes distributed randomly and uniformly over a 200x200m field
- WRx modeling based on experimental data
- Nodes powered by 2xAA alkaline batteries with capacity = 2500mAh

Performance evaluation results



(a) Energy consumption (the y axis is logscale)

(b) Average packet latency (the y axis is logscale)

(c) Packet delivery ratio

- Energy consumption: reduced up to 5 orders of magnitude
- Latency: always better than ALBA-R with duty cycle < 100%
- PDR: 100%

Expected network lifetime

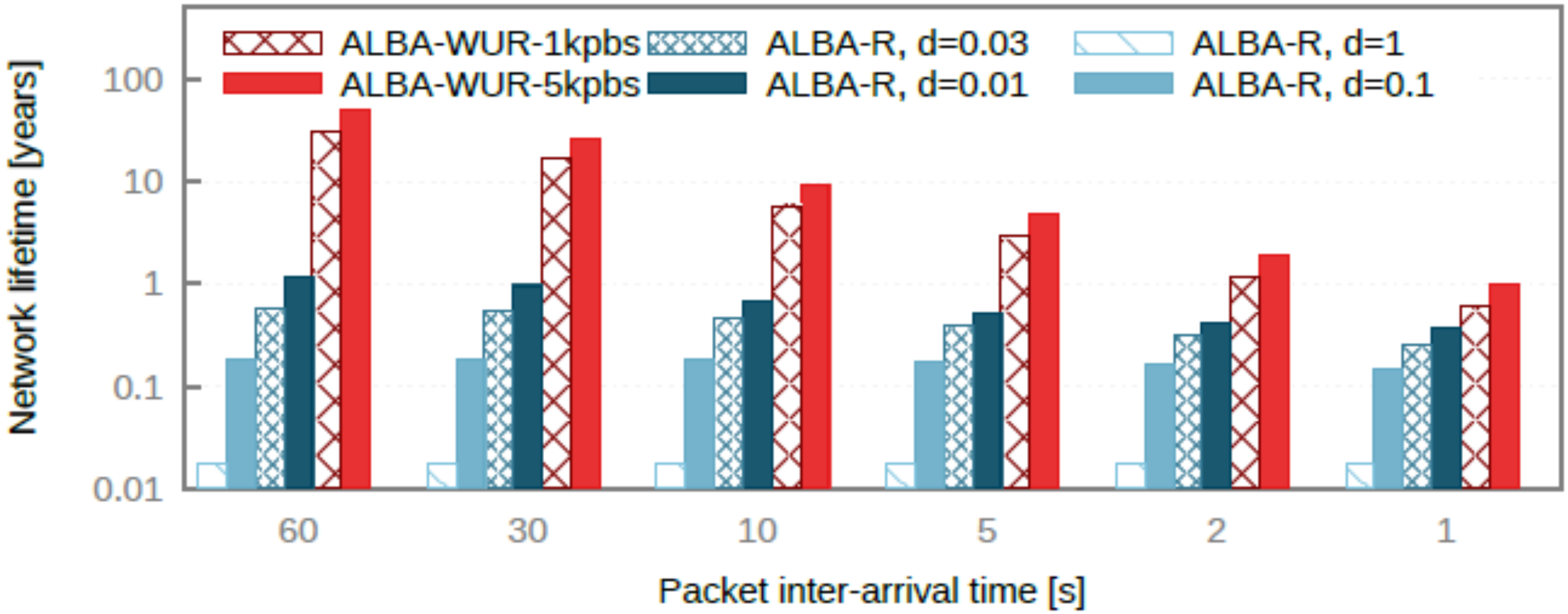


Fig. 5. Network lifetime (the y axis is logscale).

- Lifetime of **several decades**!
- Network with 1% duty cycle and **no traffic** = less than 2 years