MAC Protocols for WSNs

Internet of Things (ex Reti Avanzate), a.a. 2015/2016

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

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

S-MAC (Sensor MAC)

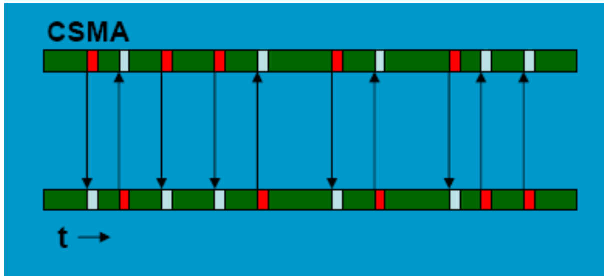
W. Ye, J. Heidemann, D. Estrin "An energy efficient MAC Protocol for Wireless Sensor Networks", IEEE Infocom 2002

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. Collision also increases latency as well.
  - *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

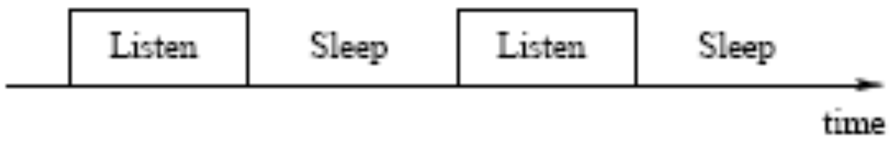


Fig. 1. Periodic listen and sleep.

- 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

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, 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 synchronize 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 thanks to t_d
    - ✓ otherwise node x selects a random time t to sleep before waking again and send this to neighbors in a SYN (x is a *synchronizer*)
    - ✓ if a node receives a different schedule after it selects its own it adopts both schedule, 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

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How do we | and synchroni

- A node p
- For node times are divided in

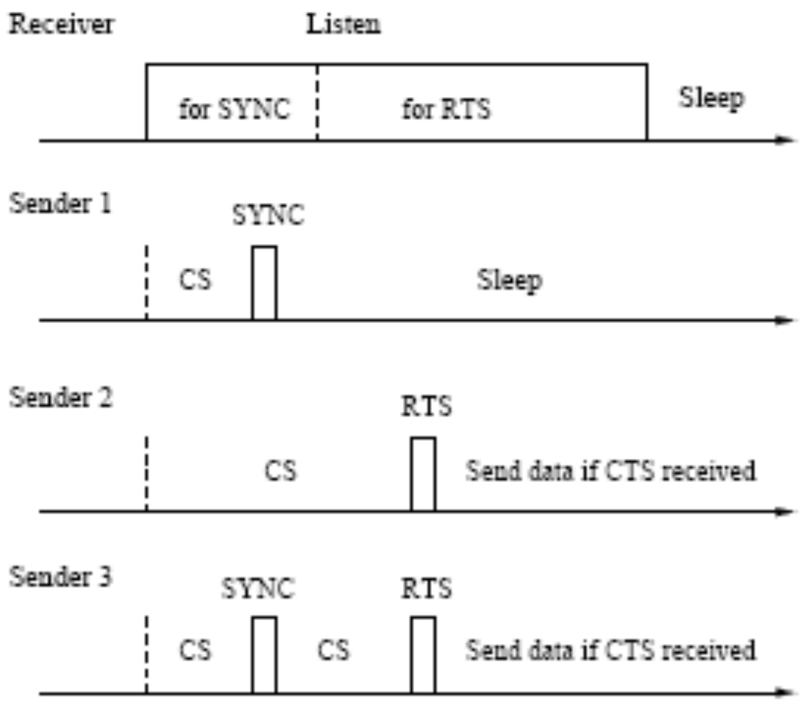


Fig. 3. Timing relationship between a receiver and different senders. CS stands for carrier sense.

S-MAC: Limits

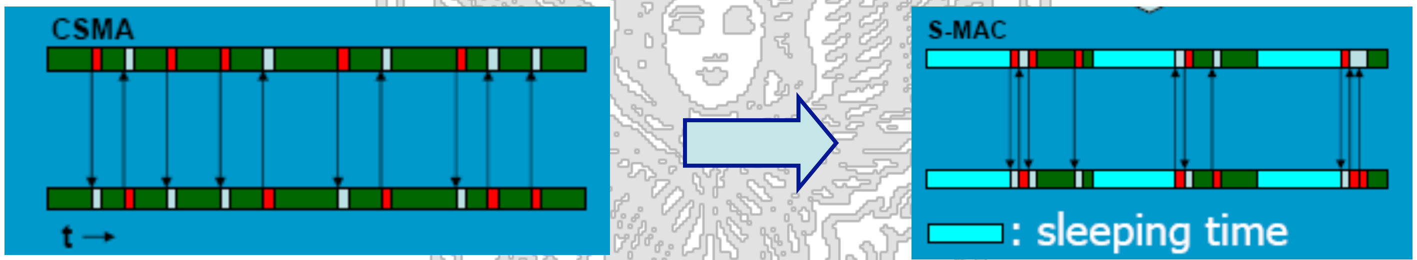
- Needs synchronization
  - even if clock drifts are not a major problem synchronization adds control overhead which may impair long lifetimes (e.g., in those applications where communication needs are sporadic)
- Throughput is reduced since only the active part of the frame is used for communication
- 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

Synchronized MAC based on duty cycle

- 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

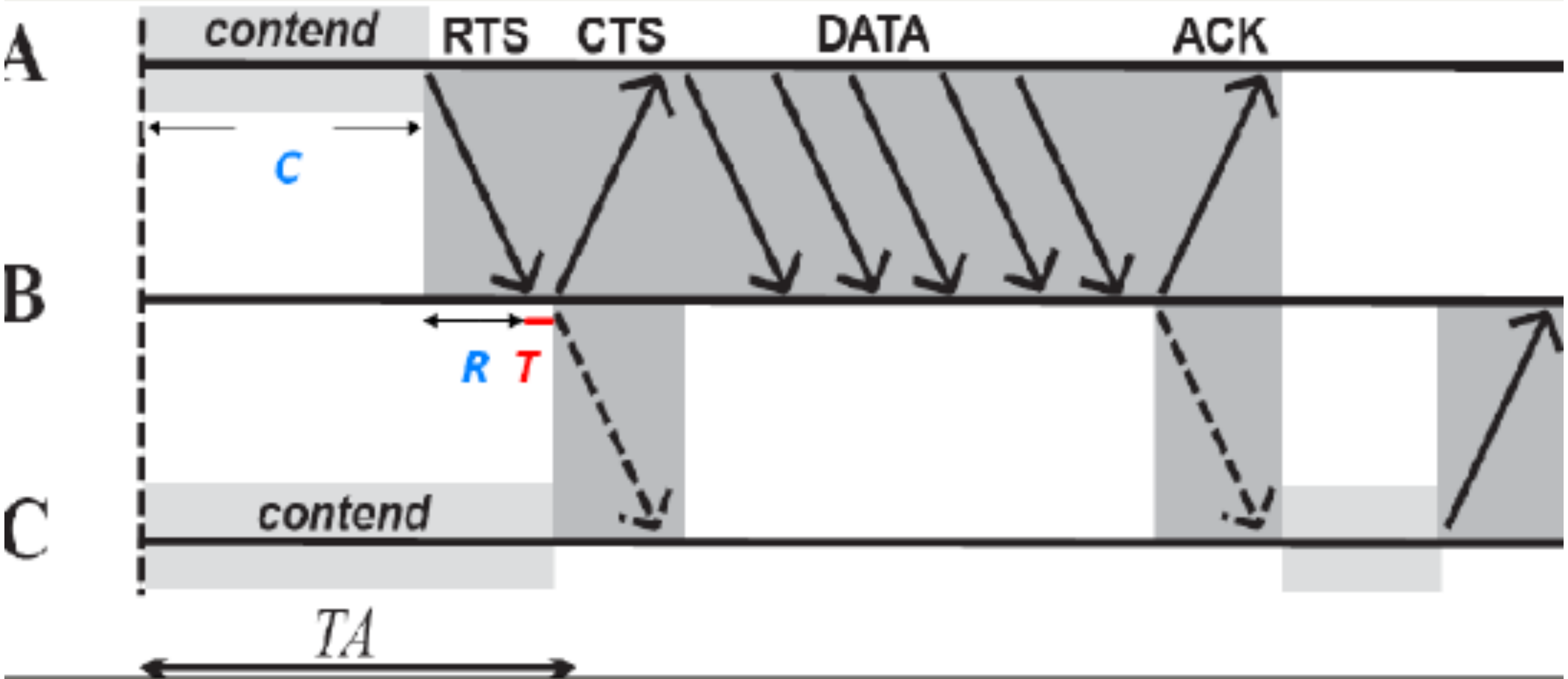
T-MAC

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

- TA timer is renewed if any data is received on the radio, communication (e.g, collision) is sensed on the radio, data are transmitted, 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
    - ✓ 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

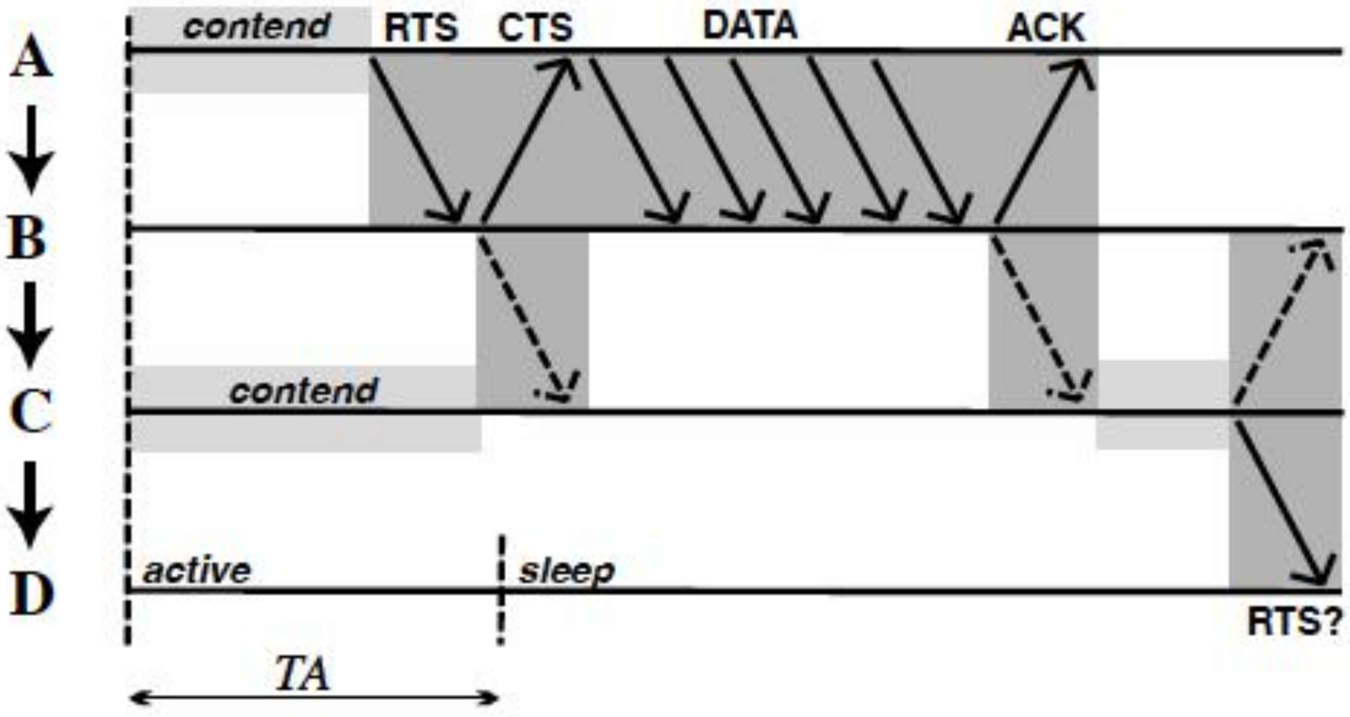


Figure 4: The *early sleeping* problem. Node D goes to sleep before C can send an RTS to it.

Early sleep- Solution 1

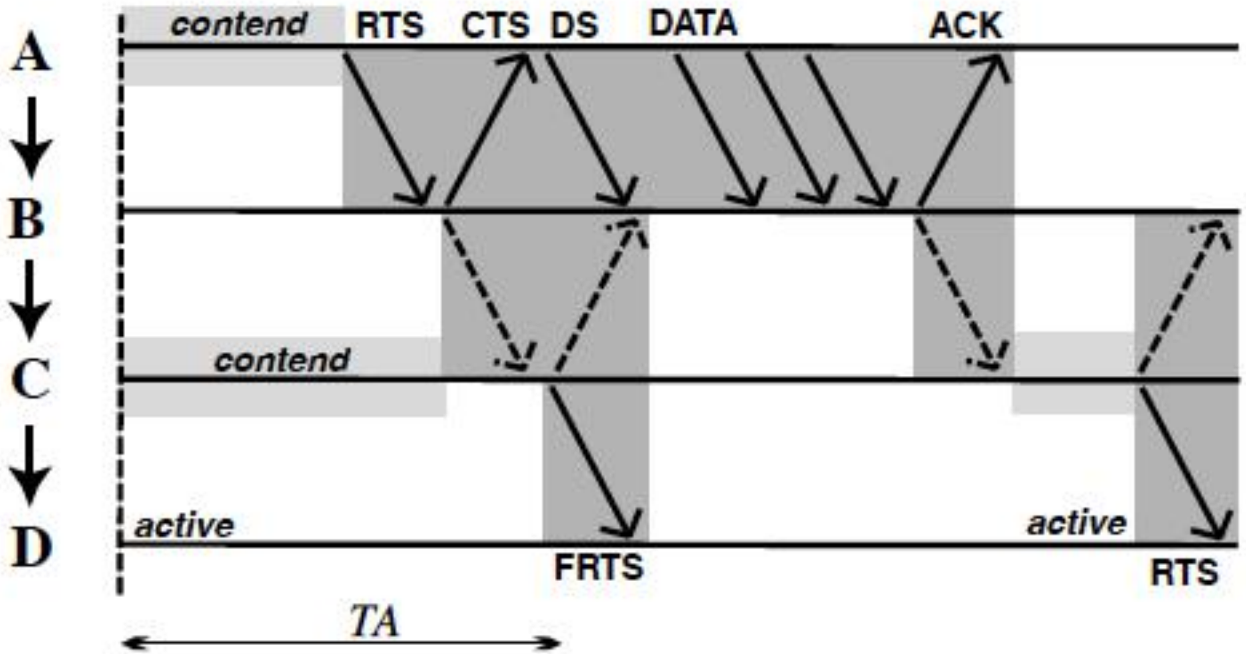


Figure 5: The future-request-to-send packet exchange keeps Node D awake.

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

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Early sleep- Solution 2

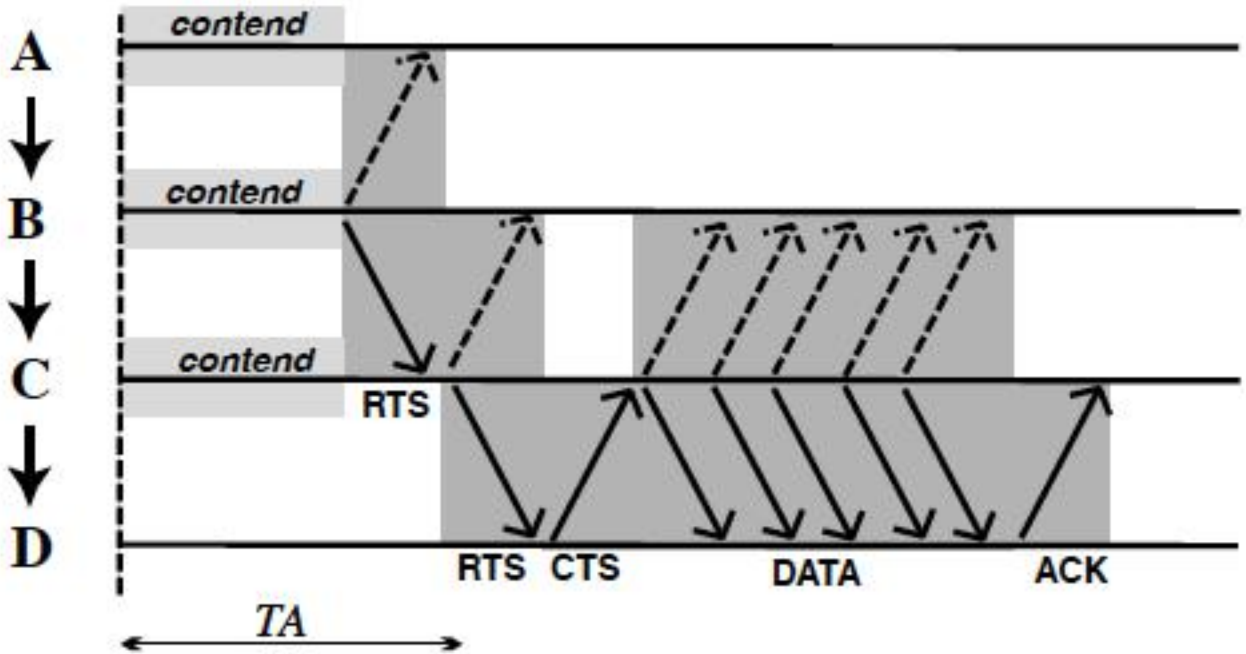
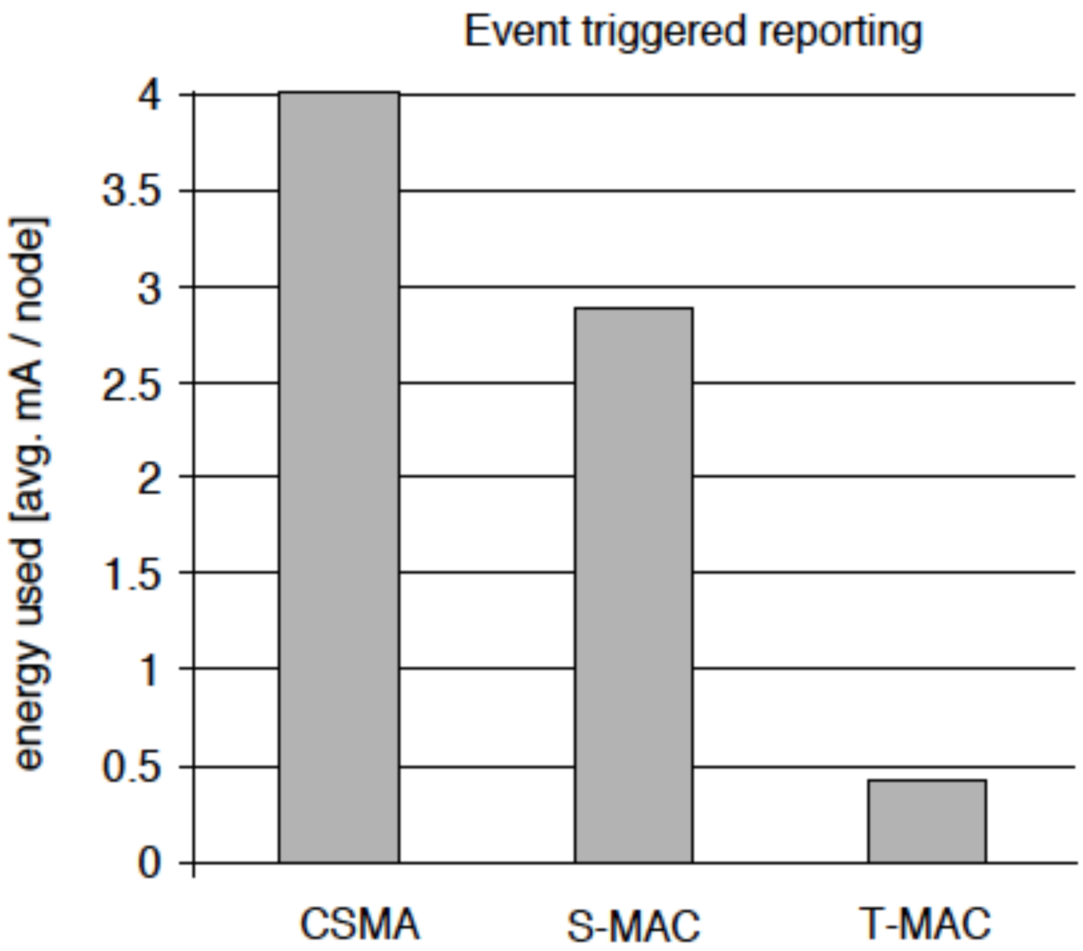


Figure 6: Taking priority upon receiving RTS.

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

- Asynchronous MAC

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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

- 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

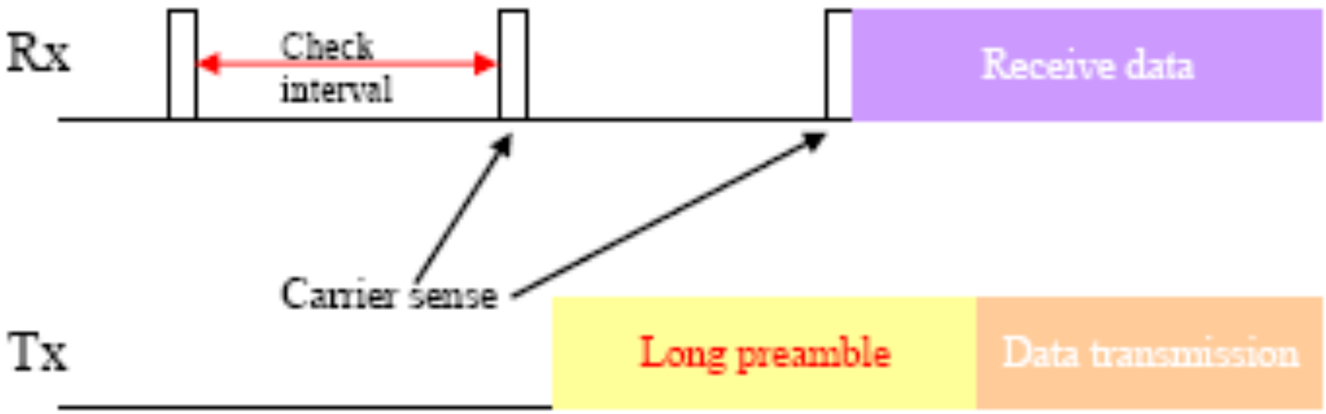
RECEIVER SIDE

- 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



Challenge

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

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

XMAC

- Ideas
  - embed address info of the intended destination in the preamble
    - ✓ to av
  - use a *s* ... short preambl ... w the destinat
    - ✓ rece ... ing short prea
      - –

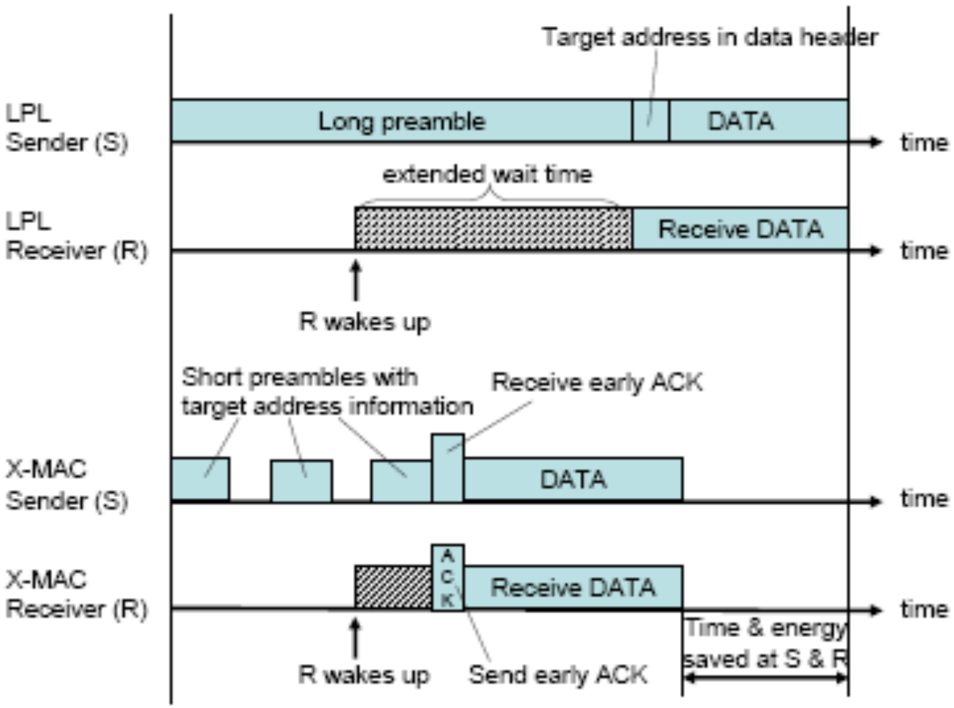


Figure 1. Comparison of the timelines between LPL's extended preamble and X-MAC's short preamble approach.

X-MAC Perf. Evaluation

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

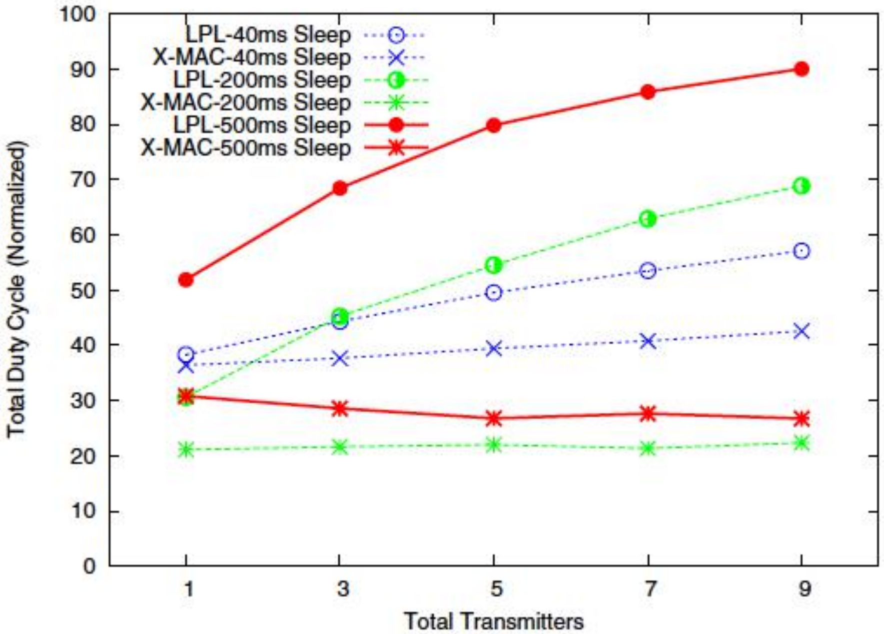


Figure 9. Duty cycle of contending senders, 1 packet per second.

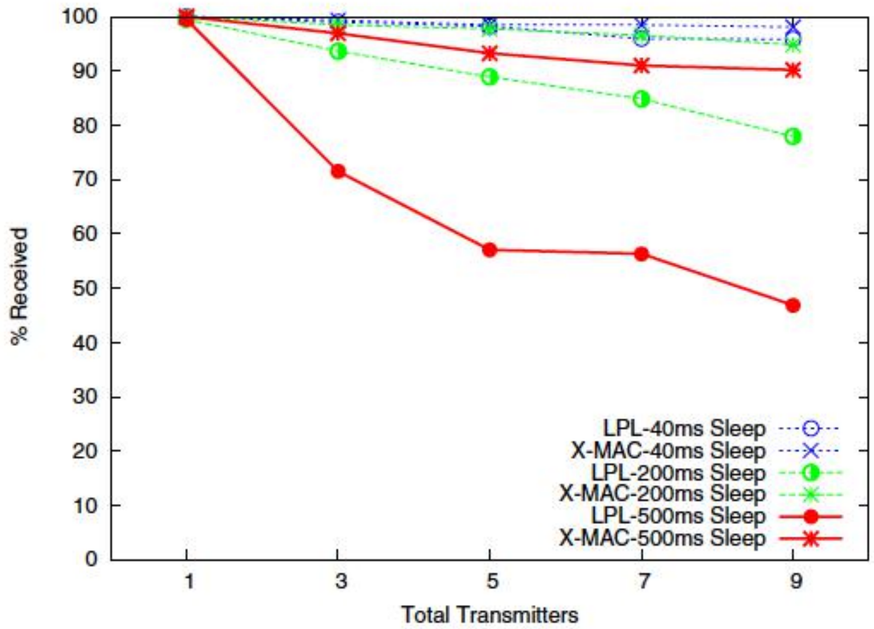
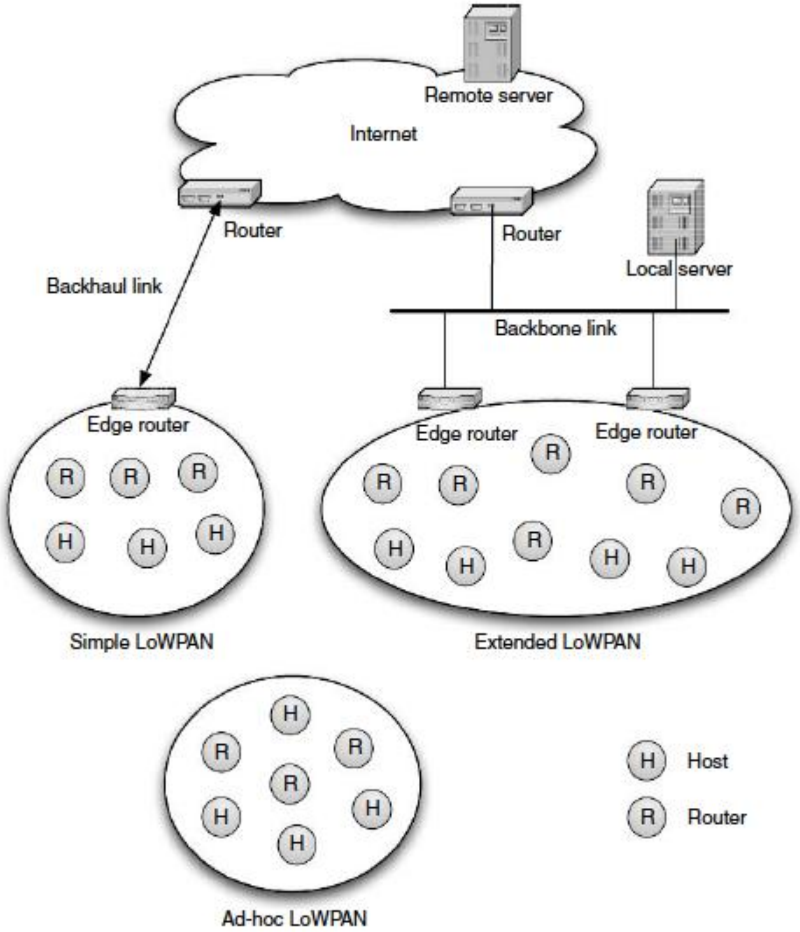


Figure 12. Reception success rate, 1 packet per second.

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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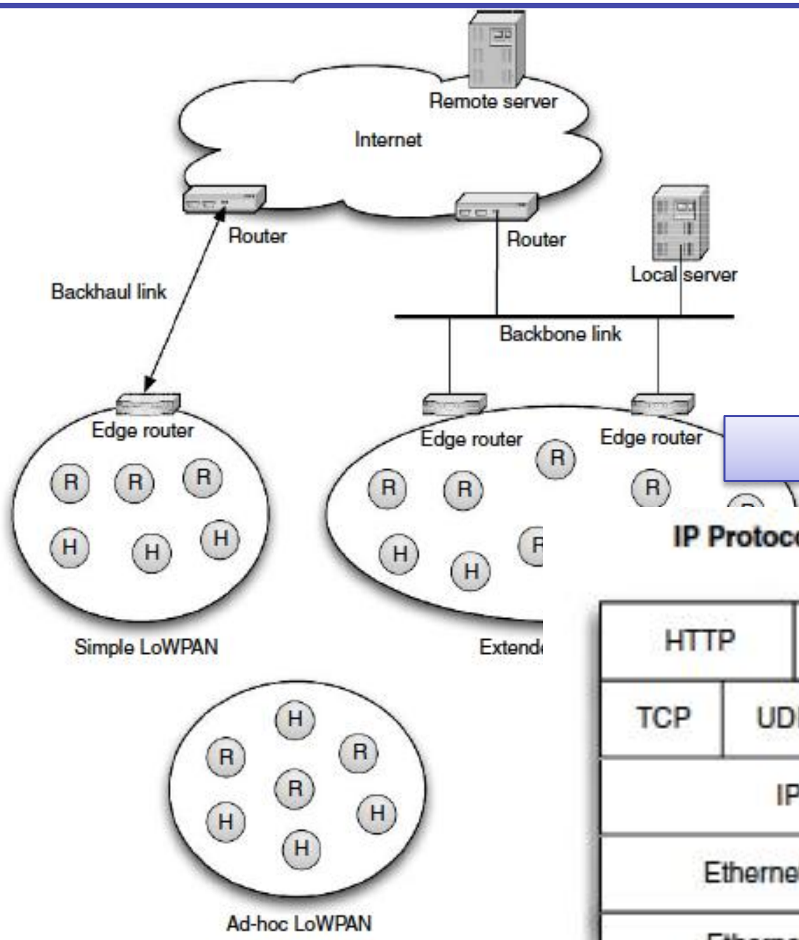
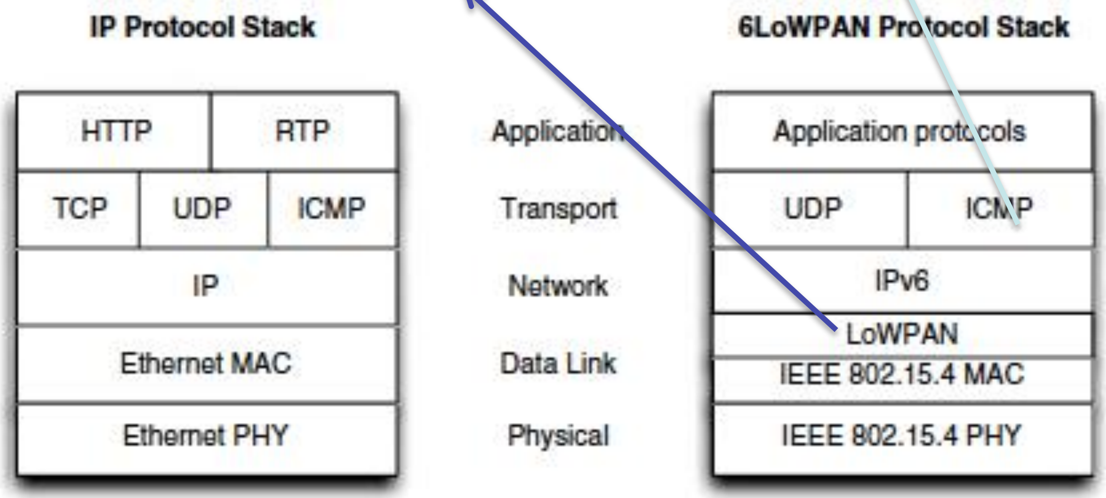


Control messages

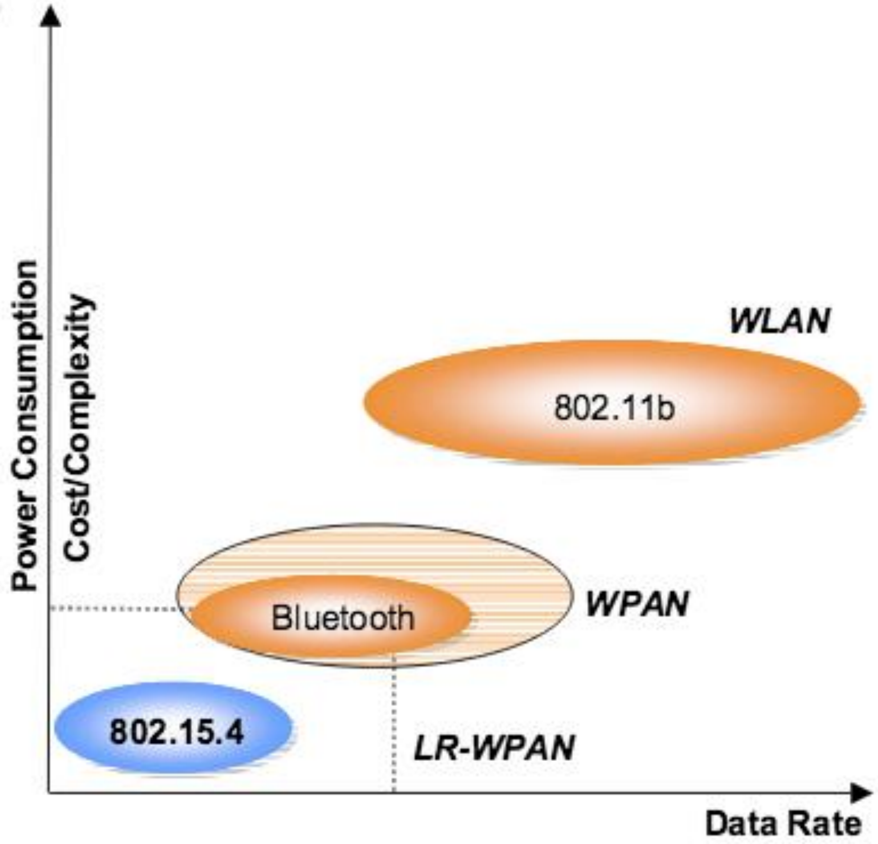
Neighbor discovery

Adaptation layer



IEEE 802.15.4

http://newyork.diet.uniroma1.it/Papers/C80-DeNardis_al-WPNC07.pdf

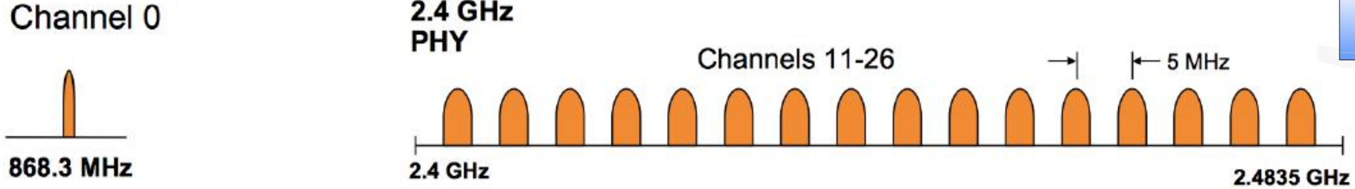


	LR-WPAN	Bluetooth™	WLAN
Range	10–30 m	~10–100 m	~100 m
Data Throughput	<0.25 MBPS	1 MBPS	~2–11 MBPS
Power Consumption	<BT/10	BT	>BT
Size	Smallest	Smaller	Larger
Nodes/Net	<<BT	BT	>BT
Cost	~$1	~$10–$15	~$40

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	

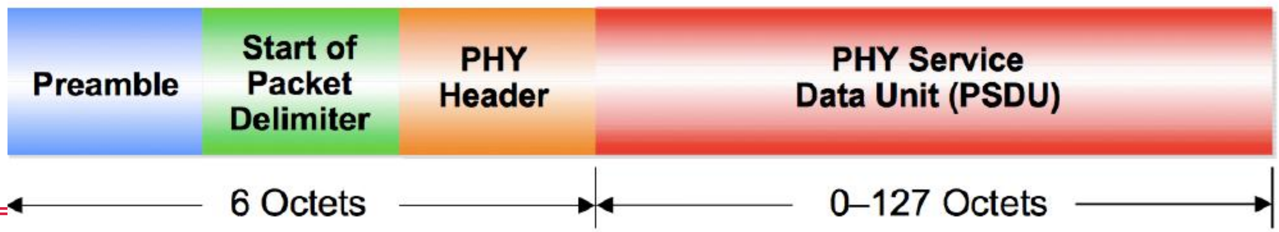
- ISM 2.4Ghz (16 channels), 868MHz (1 channel)



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

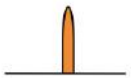
PHY Packet Fields

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



- ISM 2.4Gh

Channel 0



868.3 MHz

- 20Kbps (8
- Packet str

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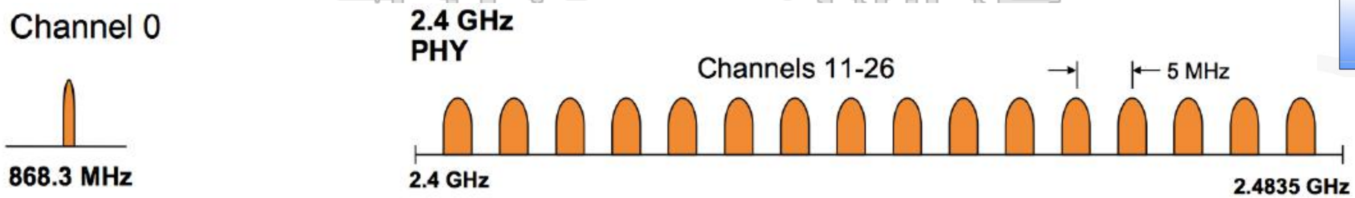

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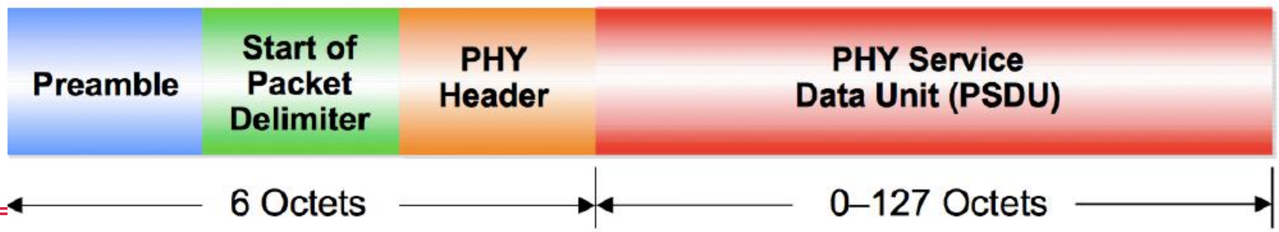
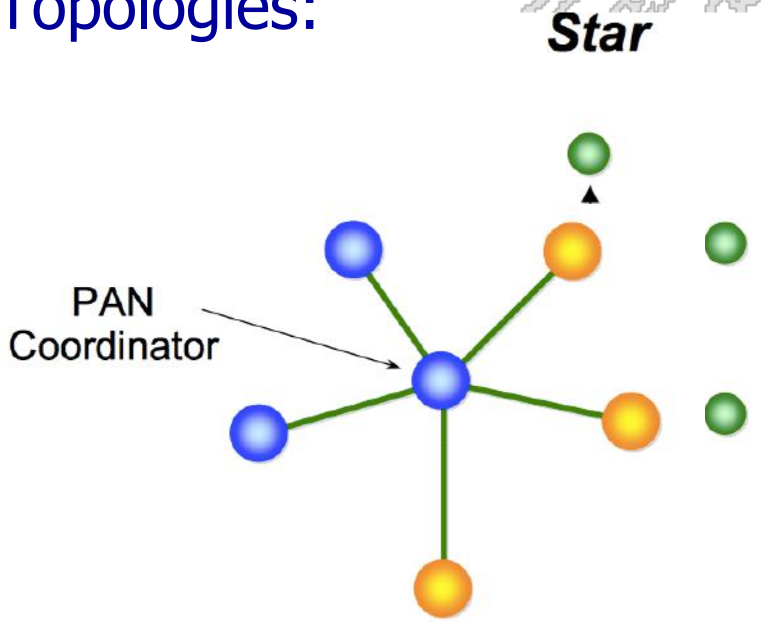
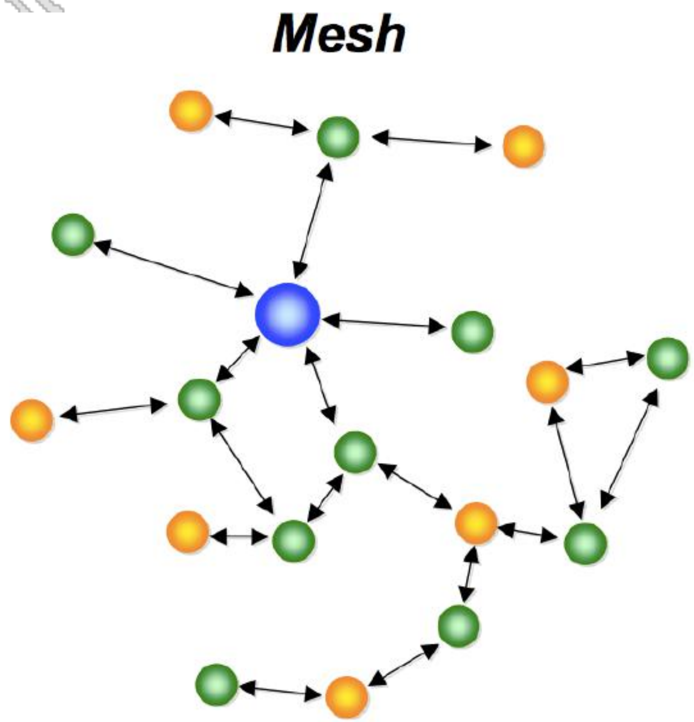


- Very low power
  - low power transmitter/receiver
  - nodes can duty cycle
- Topologies:





- Very low power operation
  - low power transmitter/receiver
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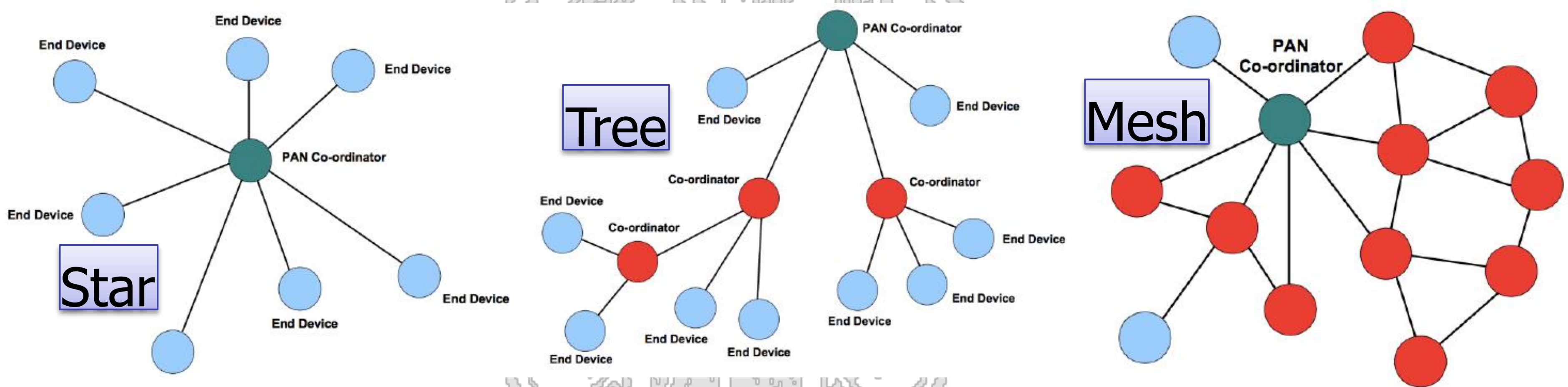
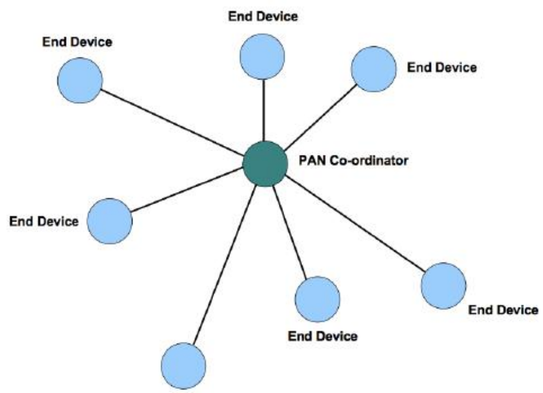
- Topologies:



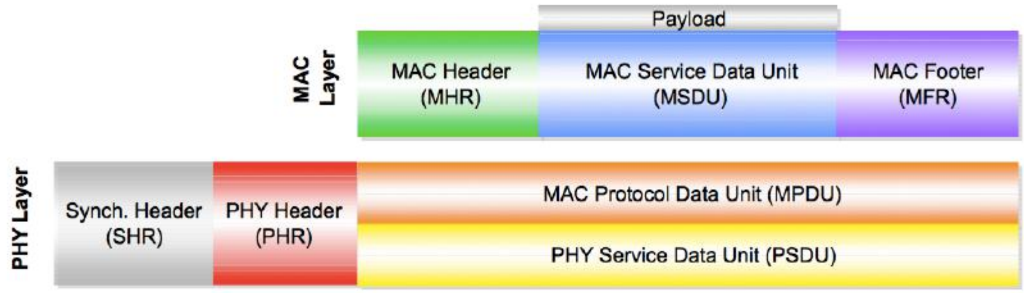
  - PAN coordinator: Net ID assignment; Frequency selection; handling request to join; packet relaying
  - Co-ordinator: handling request to join; packet relaying

IEEE 802.15.4
How a network is started

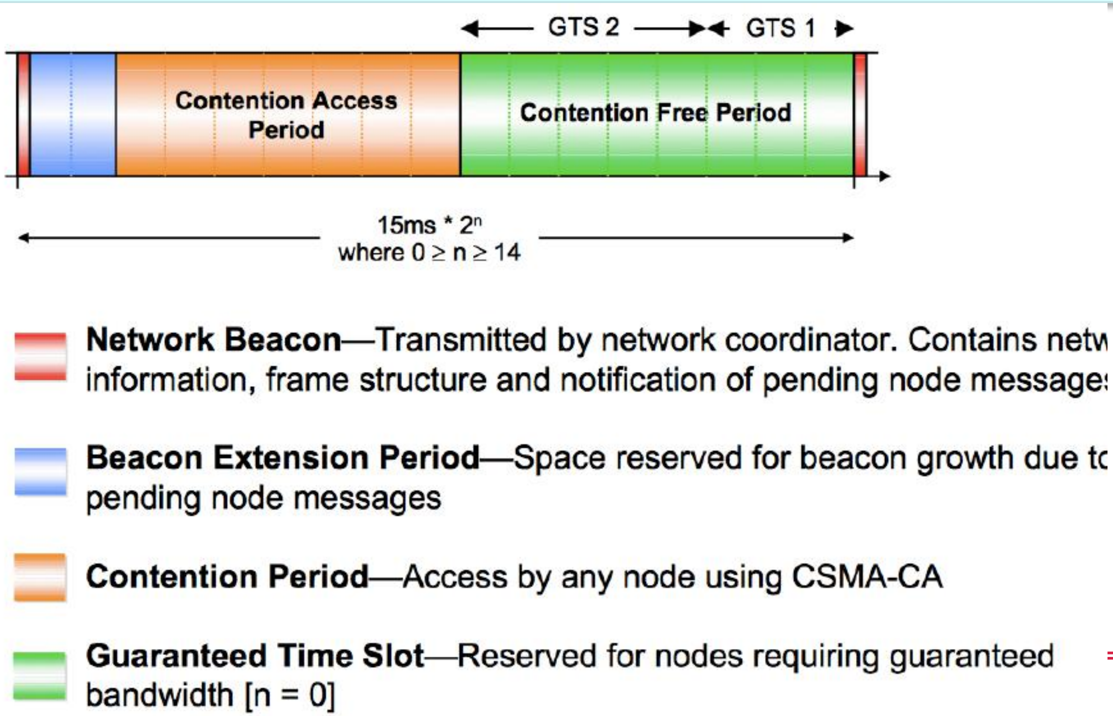
- PAN coordinator election
- PAN coordinator assigns itself a short 16 bit address (not IEEE 64 bit addresses)
- Selects the frequency
- Nodes entering the network perform active scan; discover coordinator
- Send an association request, which is ACK-ed
- PAN coordinator may assign a 16bit address to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



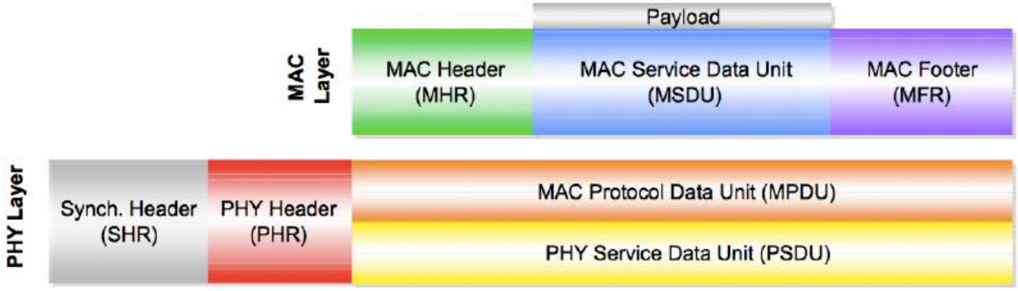
IEEE 802.15.4 MAC



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



IEEE 802.15.4 MAC



✓ CSMA/CA Based in Beaconless Mode

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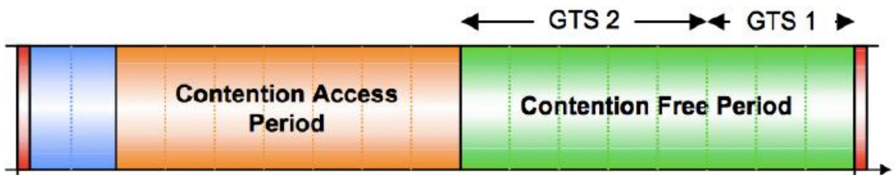


IEEE 802.15.4e envisions

Other types of MAC

Data frames for the transport of actual data, such as IPv6 frames packaged 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 operate on IEEE 802.15.4 compliant networks operating in beaconless mode

Standard-like routing Protocols for WSNs

Internet of Things (ex Reti Avanzate), a.a. 2015/2016

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

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

Collection Tree Protocol

Omprakash Gnawali (Stanford University)
with
Rodrigo Fonseca (Brown University)
Kyle Jamieson (University College London)
David Moss (People Power Company)
Philip Levis (Stanford University)

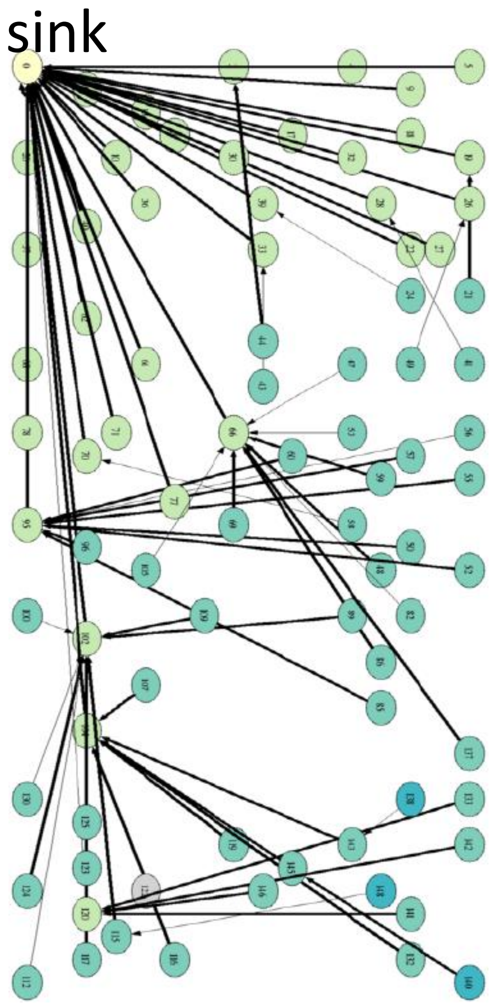
Slides partially taken from the presentation given by the authors at

ACM SenSys

November 4, 2009

Collection

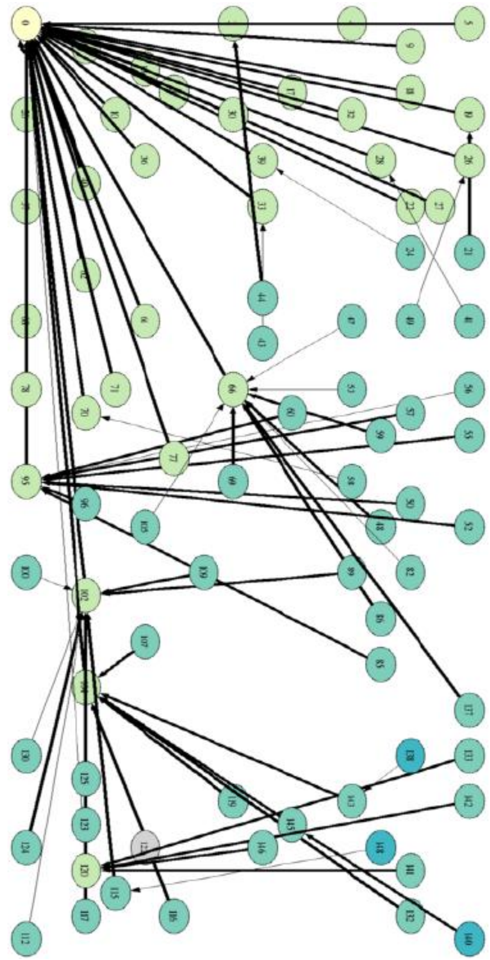
- Anycast route to the sink(s)
  - Used to collect data from the network to a small number of sinks (roots, base stations)
  - Each node selects one of its neighbors nodes as its parent
    - ✓ Parents handle packets received from the children and further forward them towards the sink
- A distance vector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



Desirable properties for collection tree protocol

- Be able to estimate and account for 1-hop link quality
- Mechanism to detect and repair routing loops
- Detect and suppress duplicate packets

sink



Common Architecture

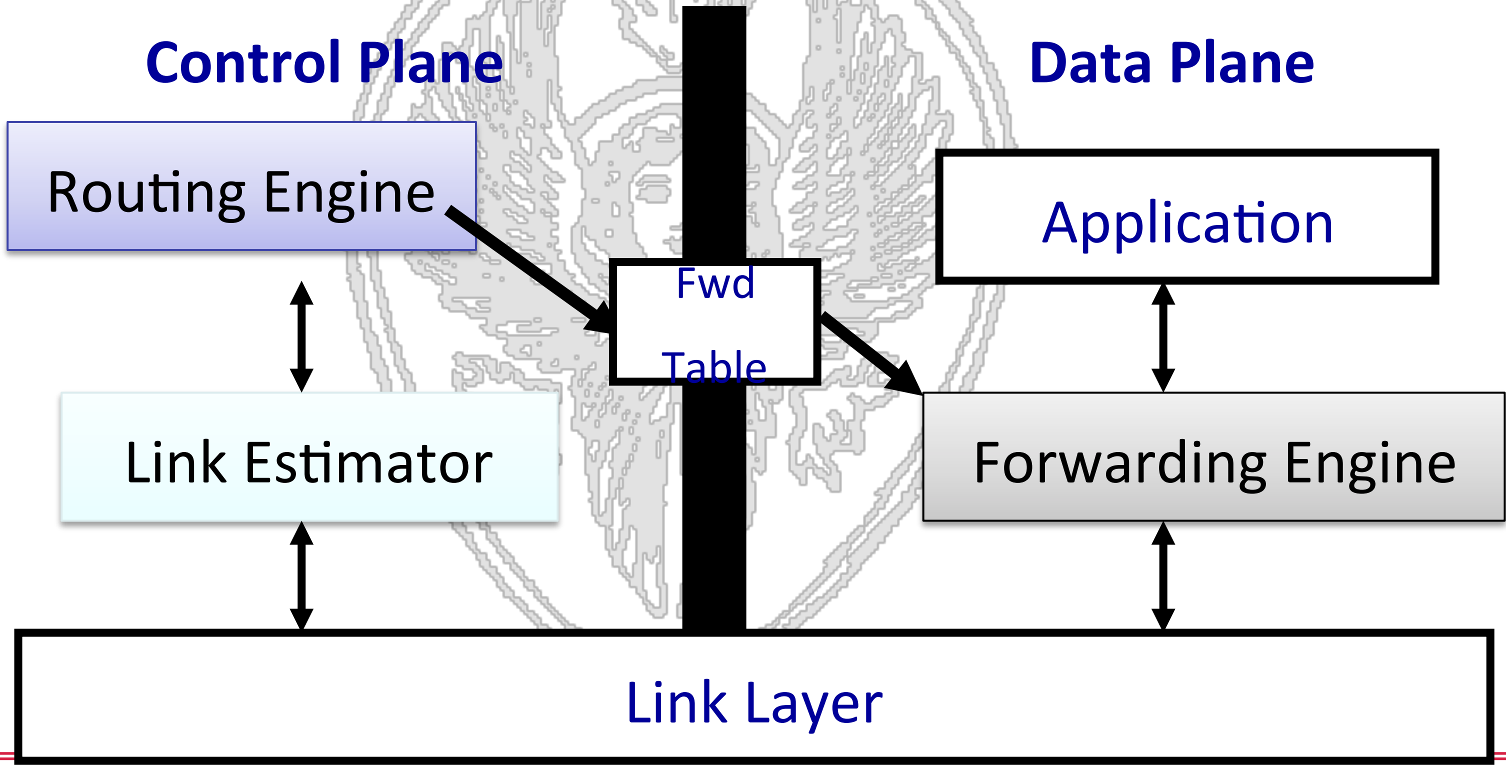
Sending and receiving beacons

for route construction and maintenance

Creating and updating the routing table

Perform forwarding

Detect and Repair Loops, filter duplicate packets



Parent selection metric

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

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

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

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

Parent selected only among uncongested nodes

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Pare

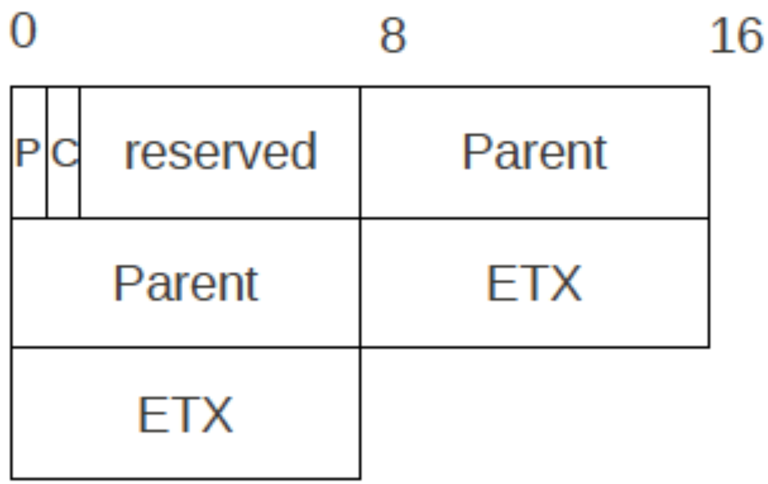
- ETX = Expected Number of Tra
- Computed based on performa past by beacon and data packe

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

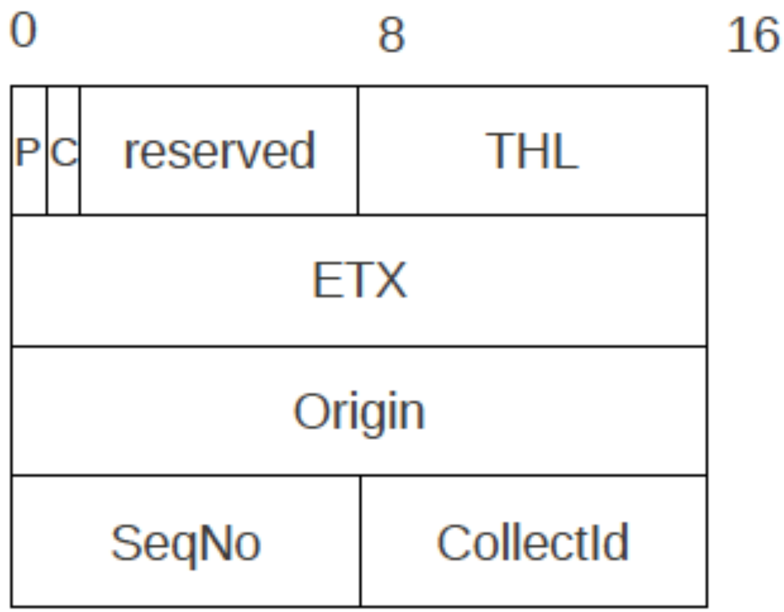
$$Q_b[k] = ($$

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

Parent selected only amor



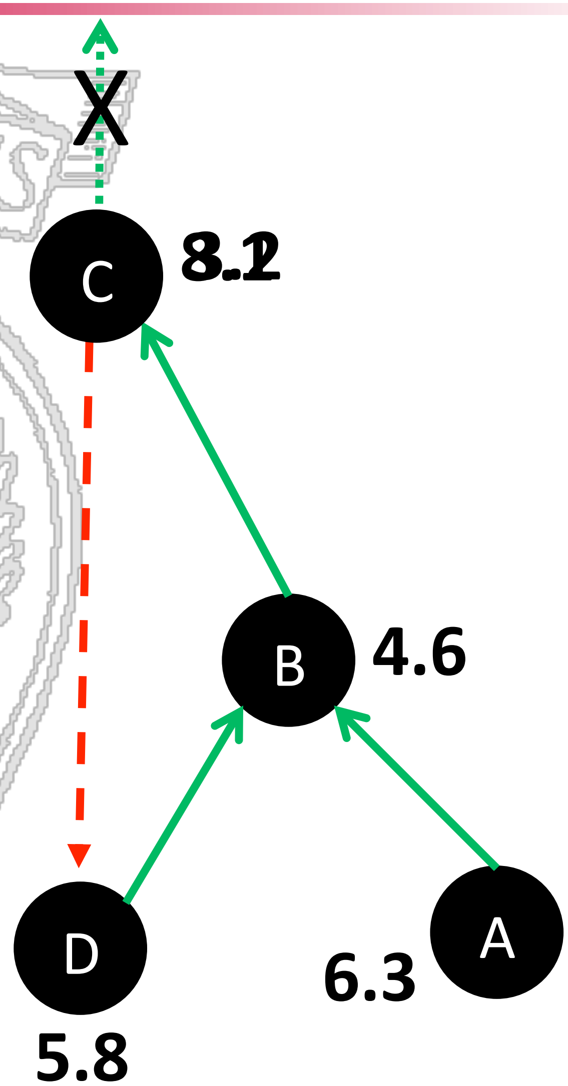
a. CTP Routing Frame



b. CTP Data Frame

Routing Loops

– Cost does not decrease

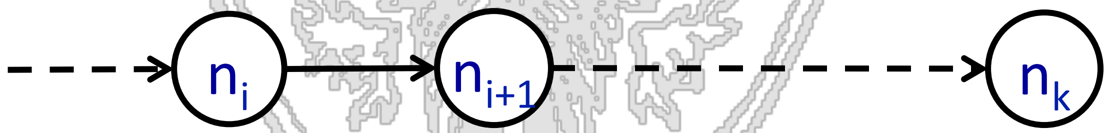


Routing Consistency

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

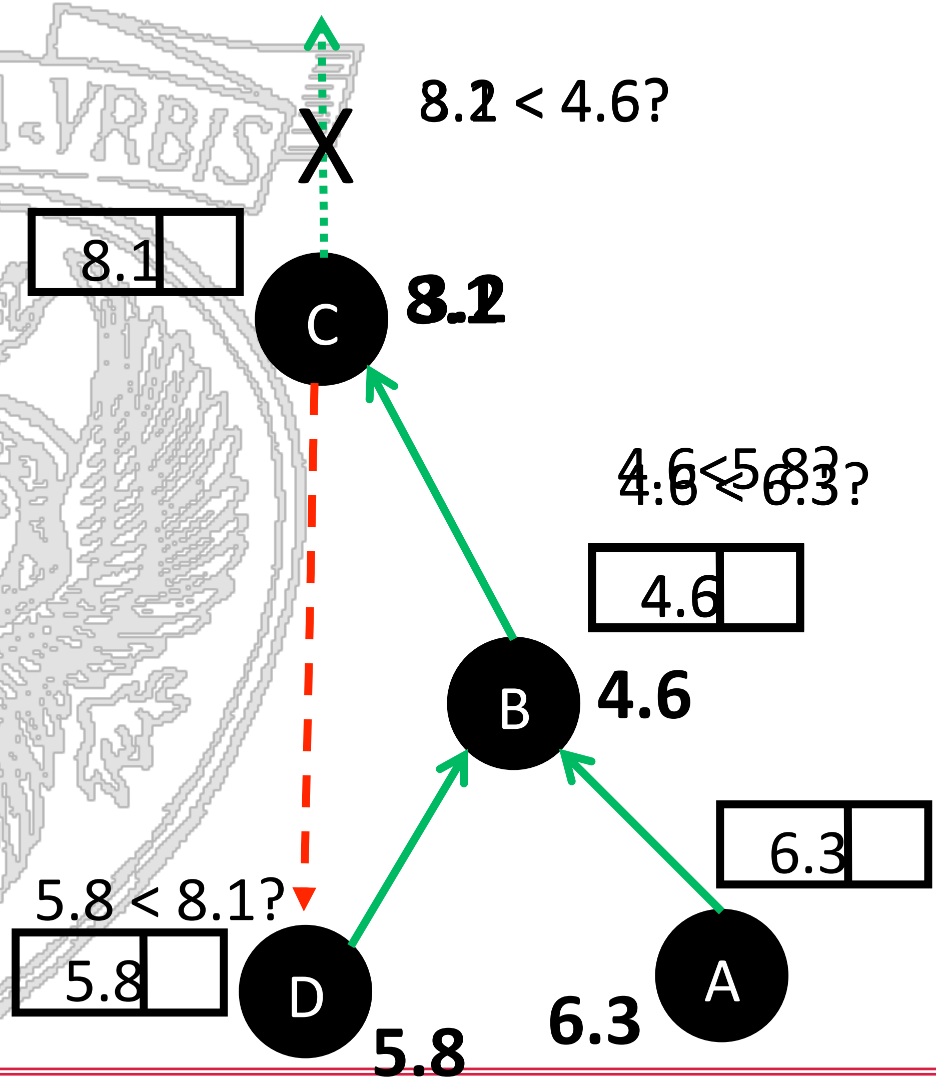
$$\forall i \in \{0, k-1\},\ ETX(n_i) > ETX(n_{i+1})$$

- Inconsistency due to stale state



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



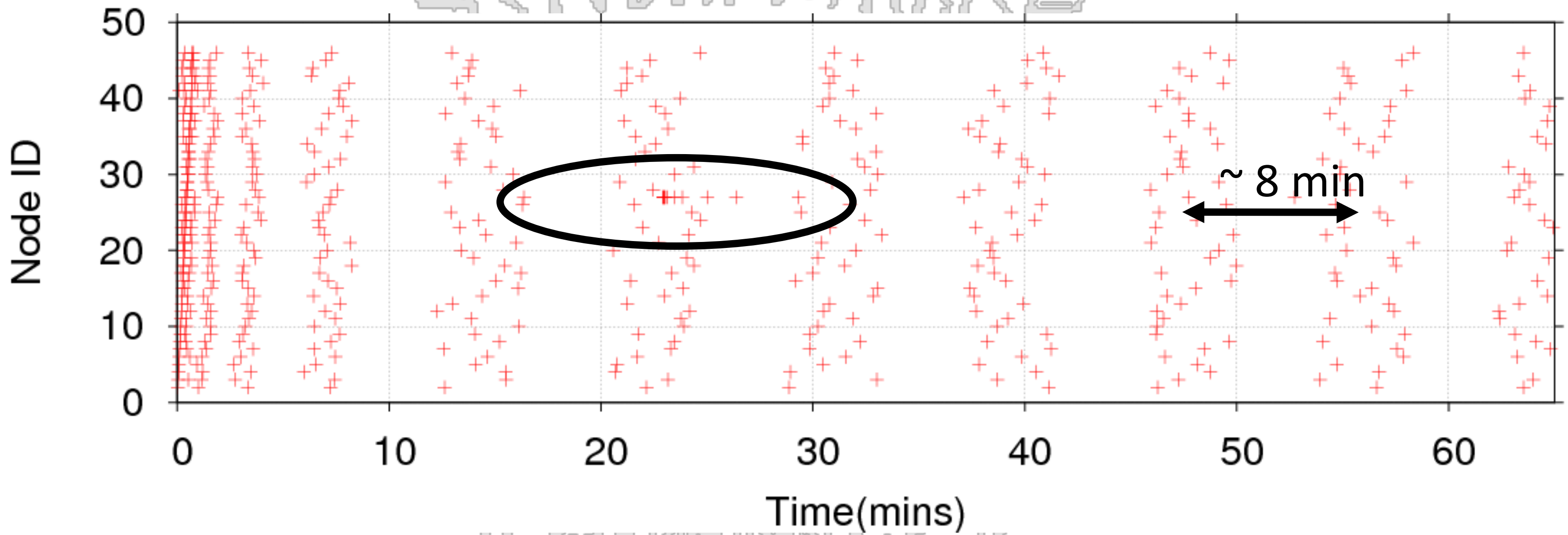
Control Traffic Timing

- 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

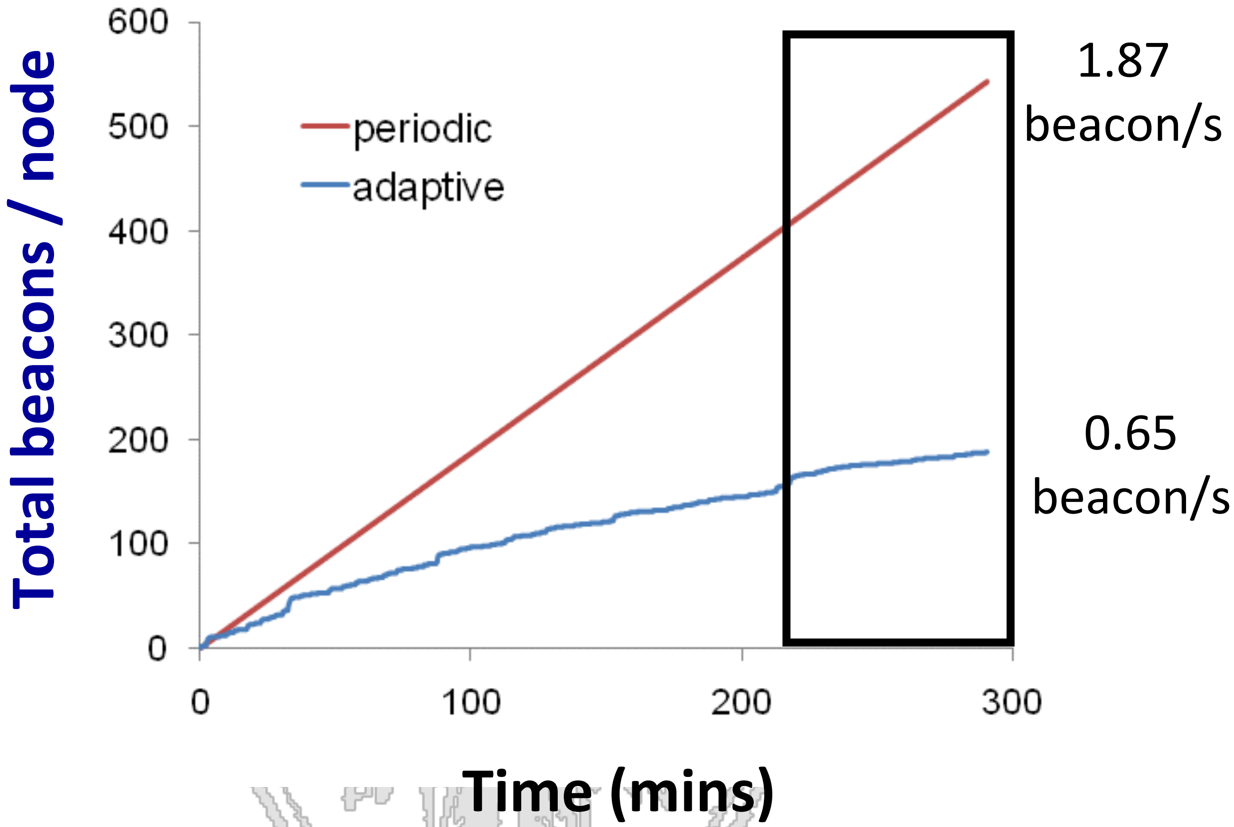
Adaptive Beacon Timing



Tutornet

Infrequent beacons in the long run

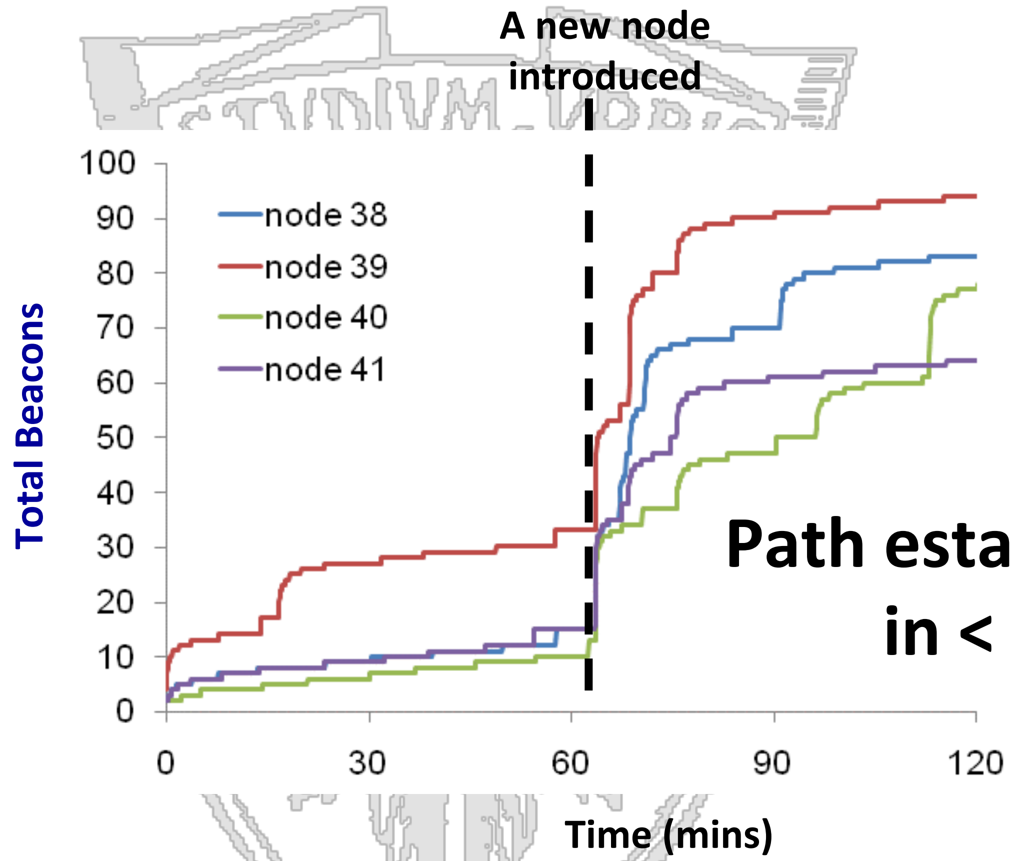
Adaptive vs Periodic Beacons



Tutornet

Less overhead compared to 30s-periodic

Node Discovery



Path established in < 1s

Tutornet

Efficient and agile at the same time

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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

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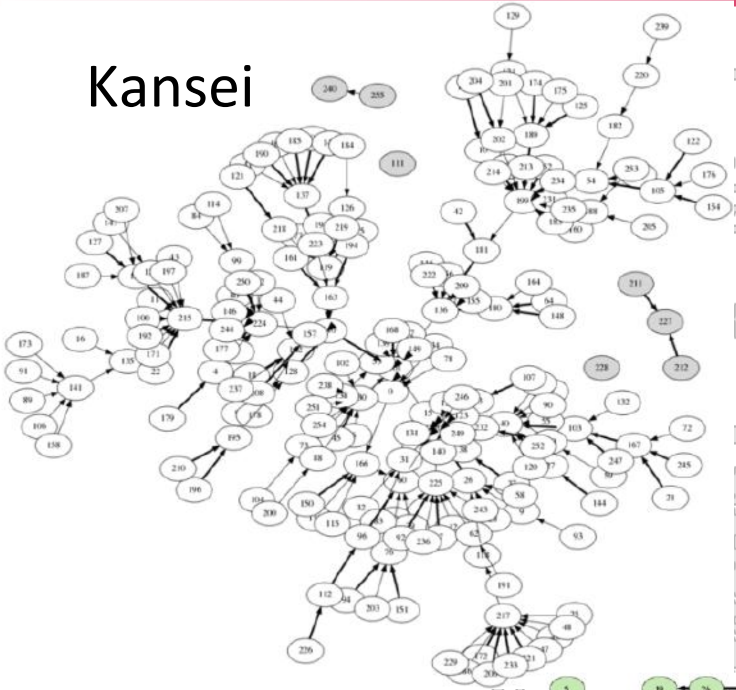
Evaluation Goals

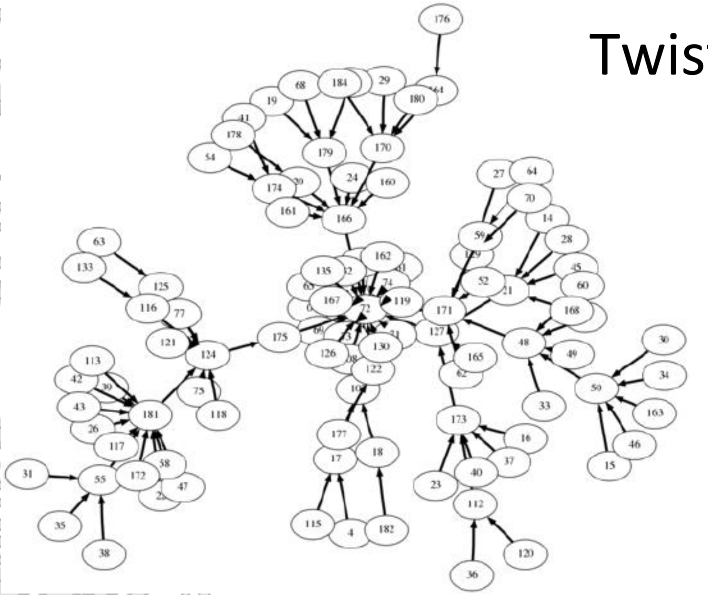
- Reliable?
  - Packets delivered to the sink
- Efficient?
  - TX required per packet delivery
- Robust?
  - Performance with disruption

CTP Noe Trees

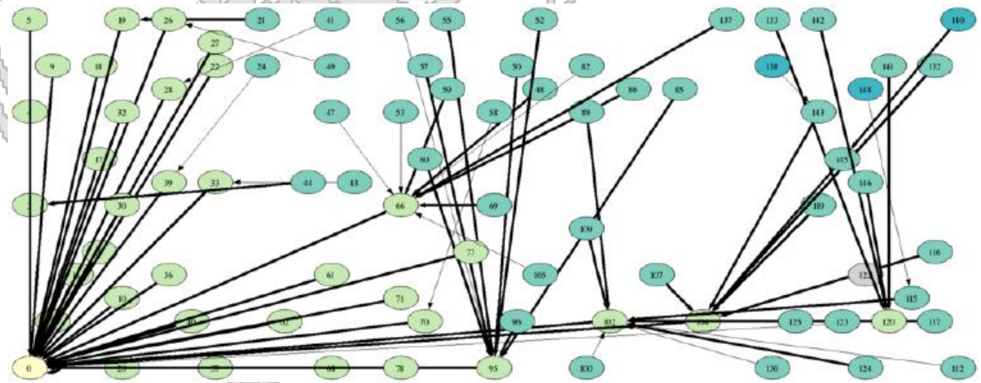
Kansei



Twist



Mirage

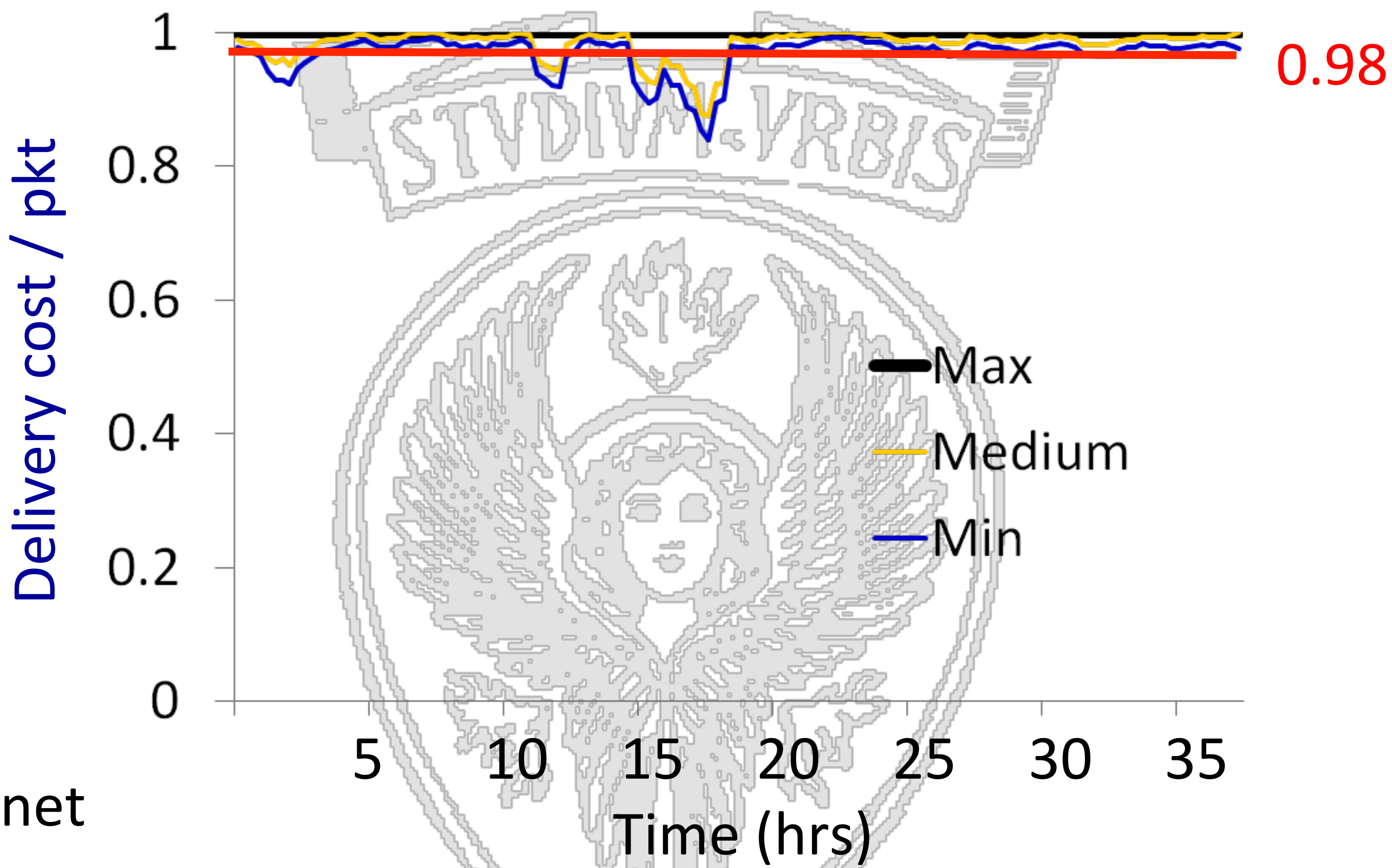


Testbed	Delivery Ratio
Wymanpark	0.9999
Vinelab	0.9999
Tutornet	0.9999
NetEye	0.9999
Kansei	0.9998
Mirage-MicaZ	0.9998
Quanto	0.9995
Blaze	0.9990
Twist-Tmote	0.9929
Mirage-Mica2dot	0.9895
Twist-eyesIFXv2	0.9836
Motelab	0.9607

False ack (Mirage-Mica2dot)

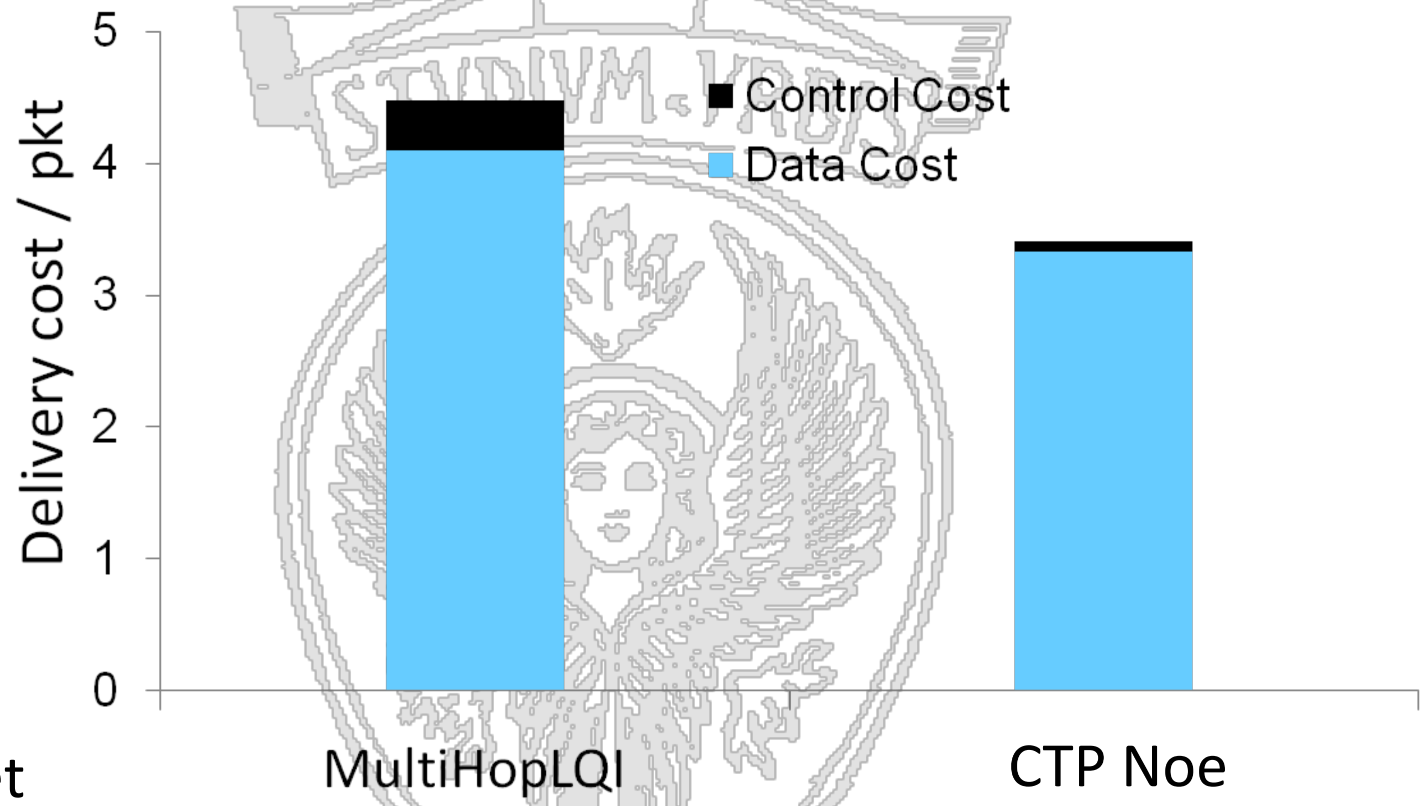
Retransmit (Motelab)

High end-to-end delivery ratio
(but not on all the testbeds!)



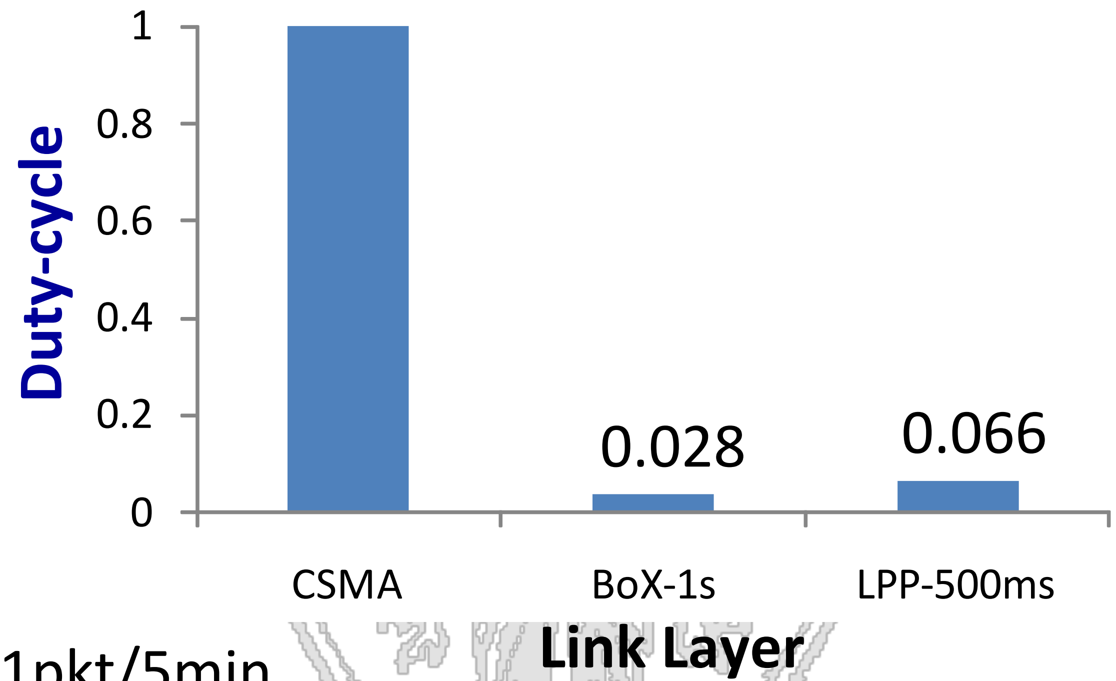
Tutornet

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



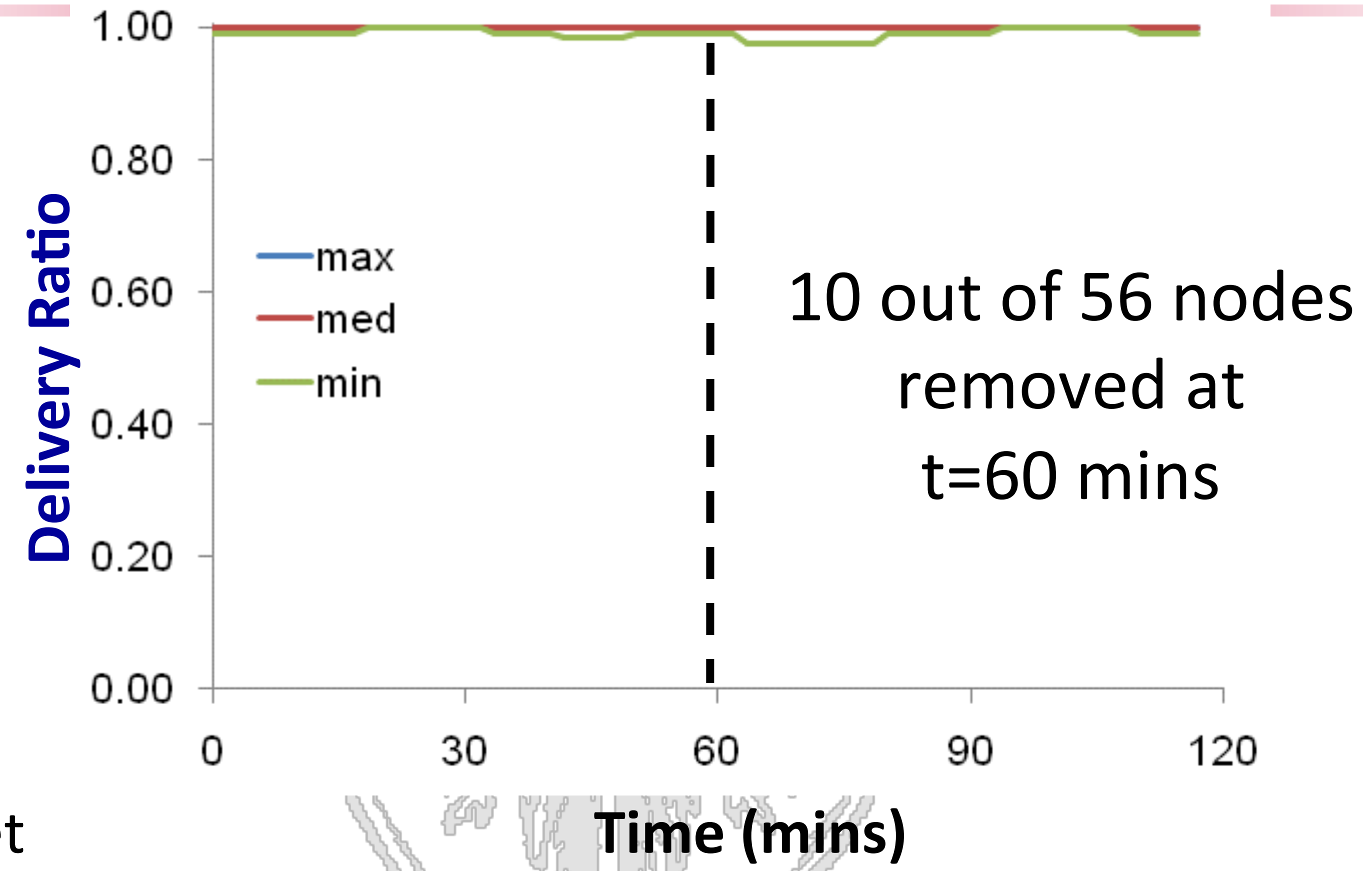
Tutornet

Low data and control cost



Motelab, 1pkt/5min

Low duty-cycle with low-power MACs

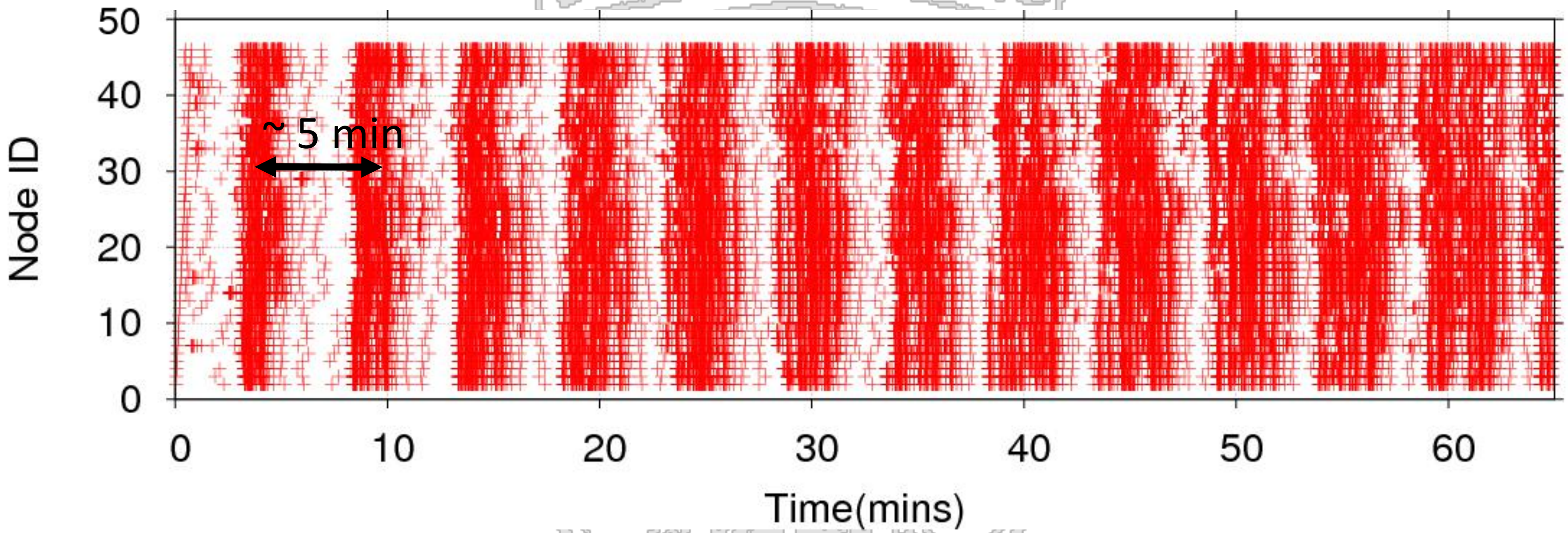


Tutornet

No disruption in packet delivery

Nodes reboot every 5 mins

Routing Beacons



Tutornet

Delivery Ratio > 0.99

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

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

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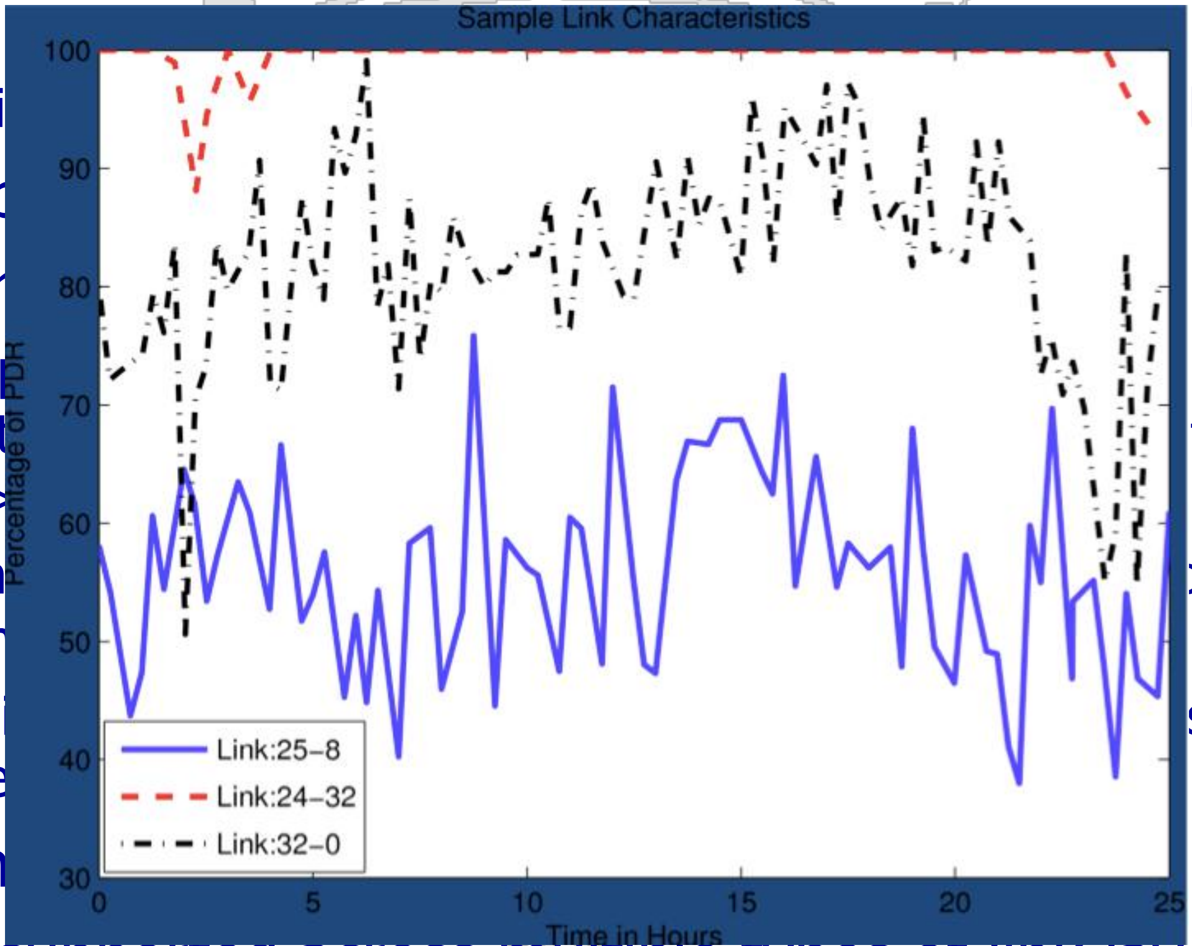
ROLL--Routing Over Low power and Lossy

- “Ripple” routing protocol RPL-- Proactive distance vector routing;
  - specifi … h (DODAG)
- Multi-hop
- Flexible r
  - <Find … links> or <Find t … ttery operated nodes>
  - Admin … ogies active at the sam
  - dynami … s, all fast change
- Focus on



- Routing supported across multiple types of link layers

ROLL--Routing Over Low power and Lossy

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

RPL– DODAG formation

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

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

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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)
- DAO messages are forwarded till the root
- Prefix reachability info exchange also enables peer to peer communication
  - up along the tree till the common ancestor, then down till the intended destination

RPL –trickle timers

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

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

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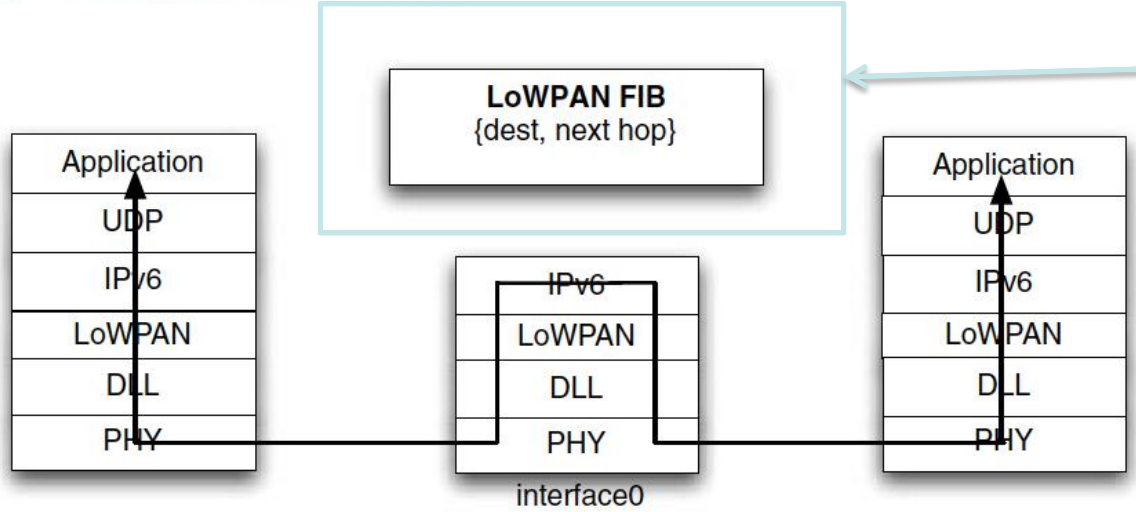
6LoWPAN Routing

Updated by the Selected routing protocol




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

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

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

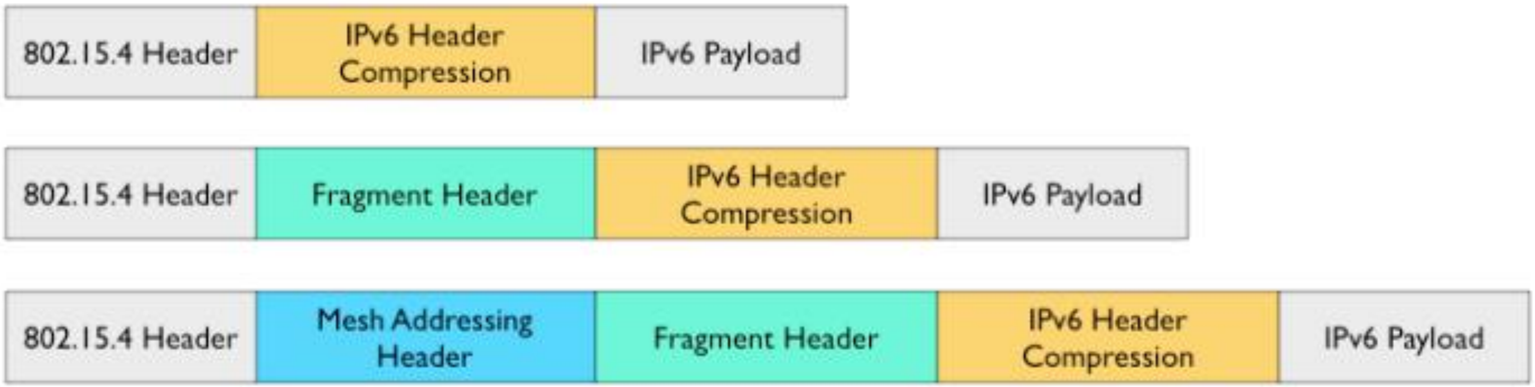


Figure 2. Typical 6LoWPAN Header Stacks.

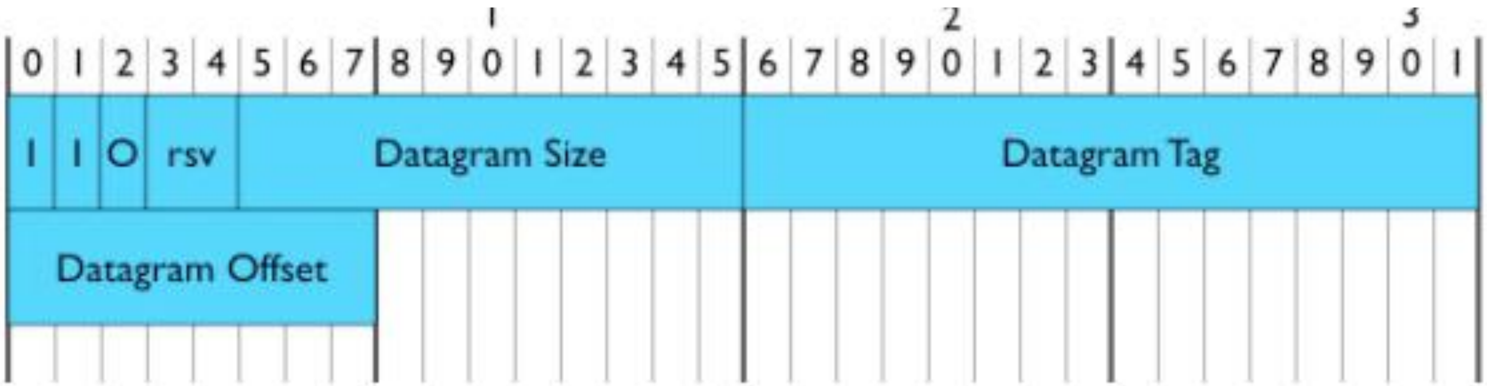


Figure 3. 6LoWPAN Fragment Header.

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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.

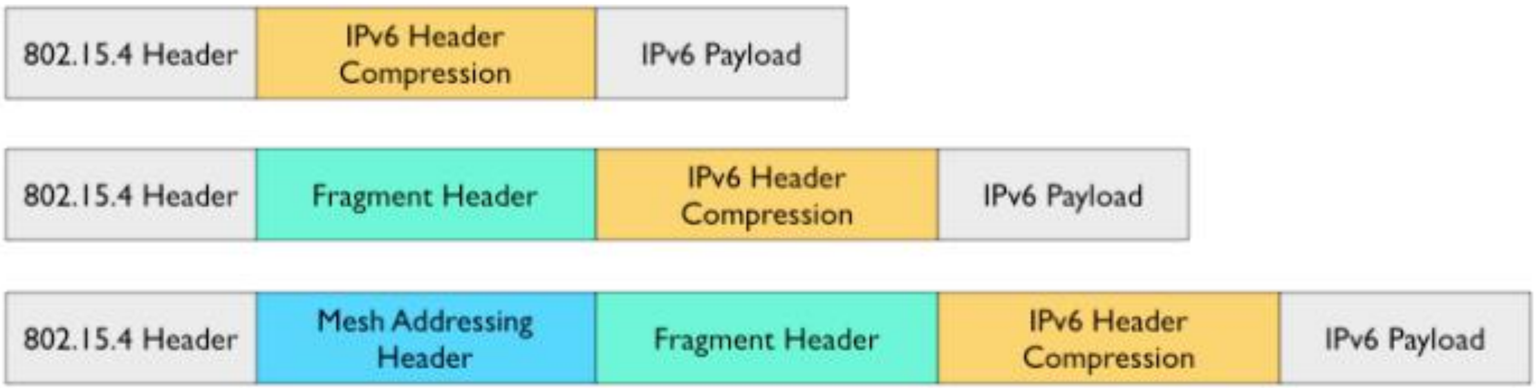


Figure 2. Typical 6LoWPAN Header Stacks.

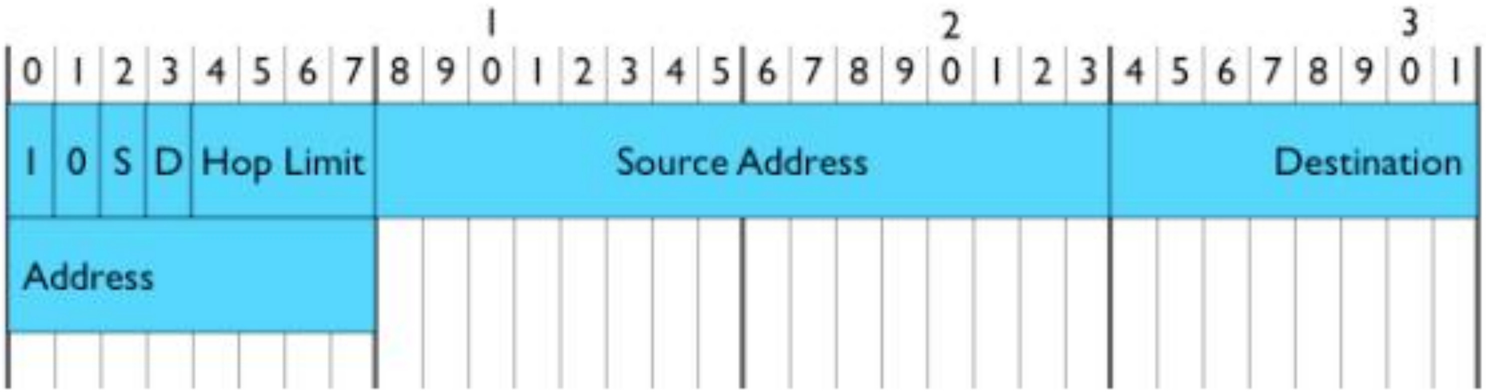
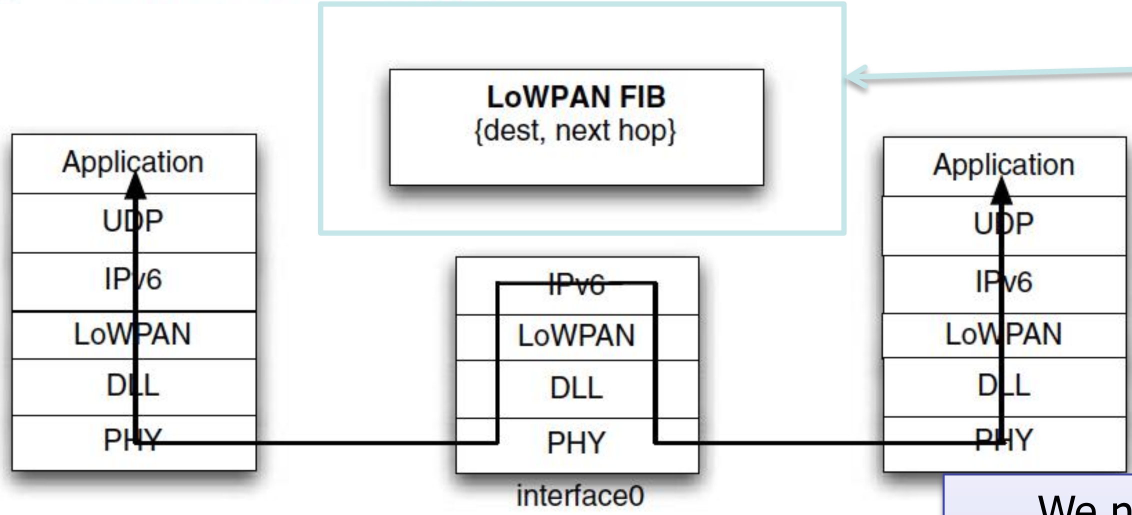


Figure 4. 6LoWPAN Mesh Addressing Header.

6LoWPAN Routing

Updated by the Selected routing protocol



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)

```
 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  _/
```

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

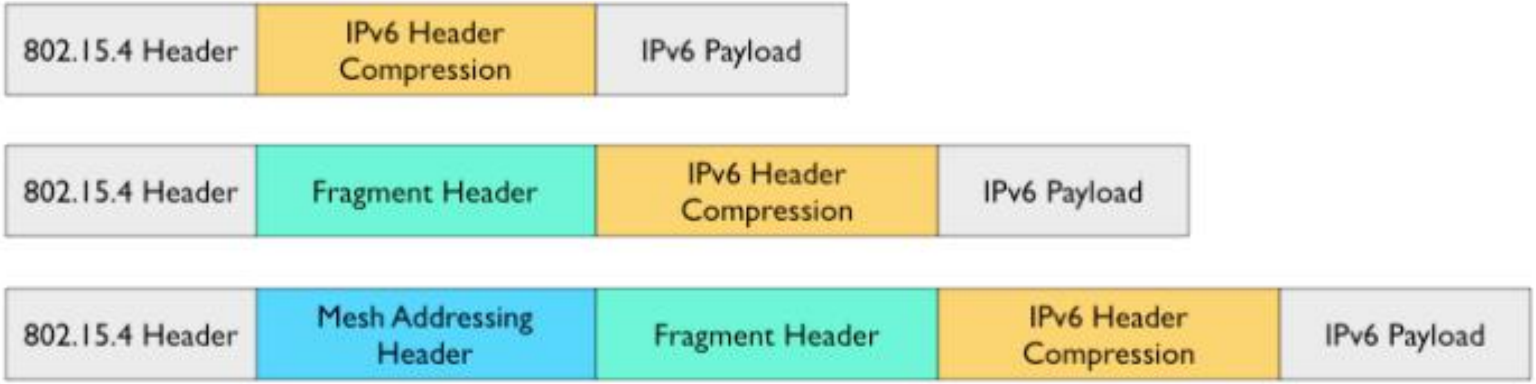


Figure 2. Typical 6LoWPAN Header Stacks.

Figure 5. 6LoWPAN RFC 4944 IPv6 Header Compression.

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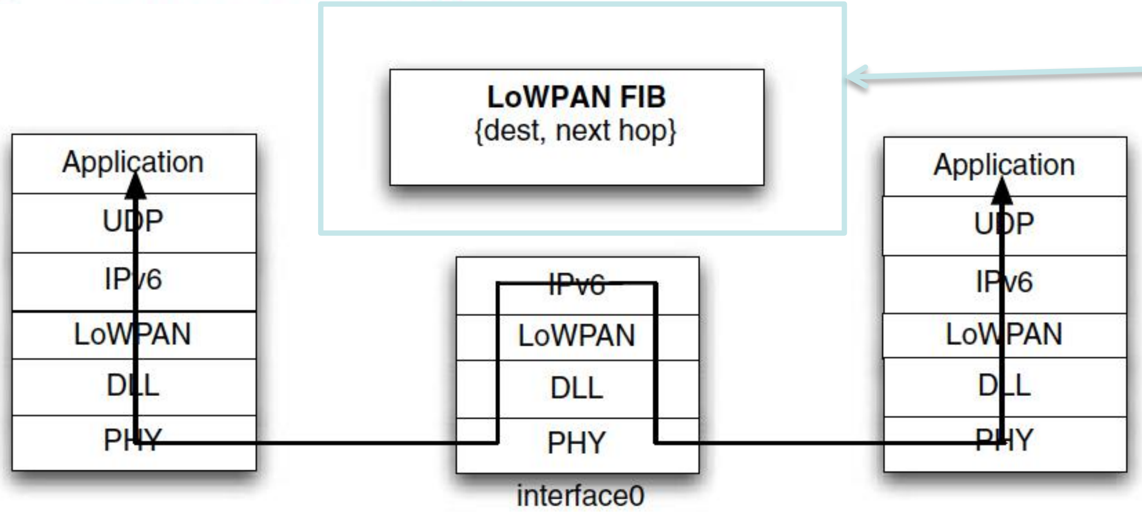
6LoWPAN Routing

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

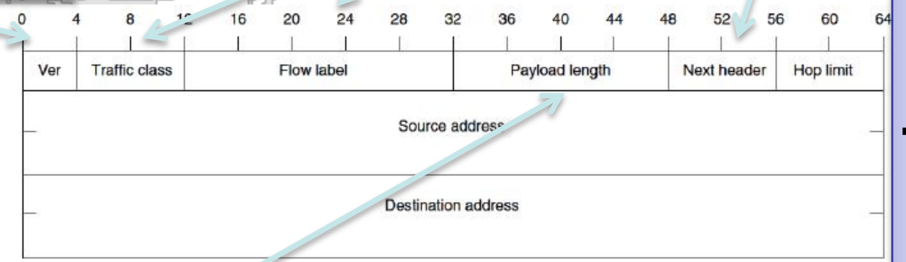
Always 6 not transmitted in HC1

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

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |0|       Non-Compressed fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/ \_ HC1 header_/

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



IPv6 packet header

Can be inferred by other Headers--Not transmitted

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Header Compression

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

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |0|       Non-Compressed fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch   _/ \_ HC1 header_/
```

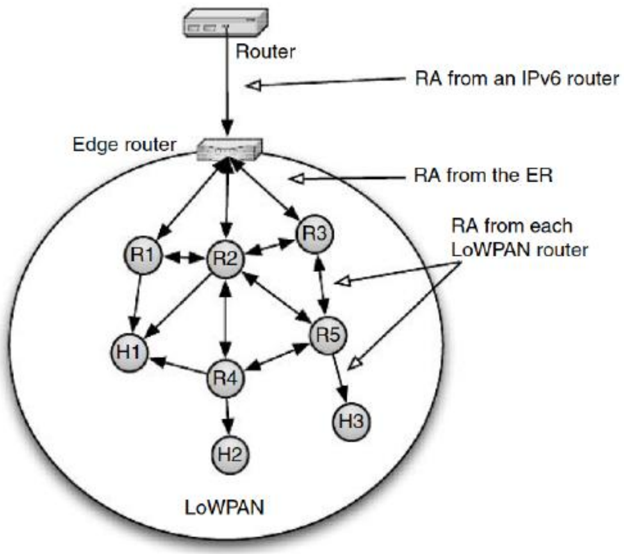
```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0 1 0 0 0 0 1 0|SAE|DAE|C|NH |1|S|D|L|__________| N.-C. fields...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+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

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

Indicates length size can be inferred and is thus not included

Bootstrapping an IoT network

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

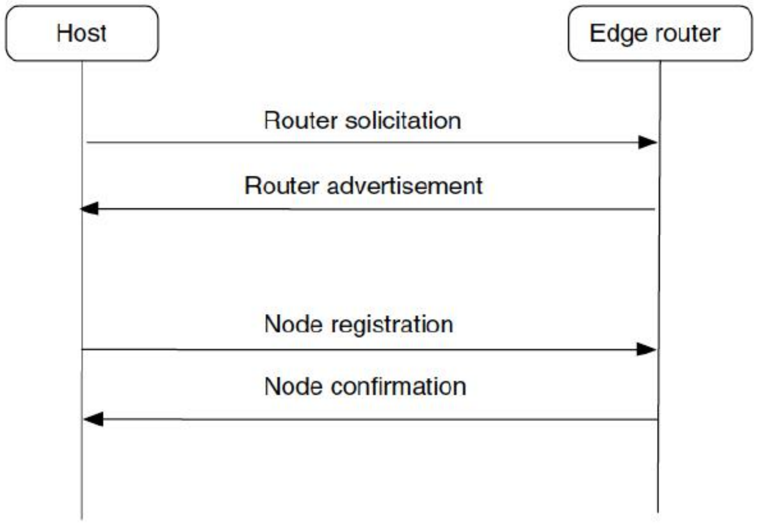



```
 0                   1
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|0|1|LOWPAN_BC0 |Sequence Number|
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 \_ dispatch  _/
```

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      |
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|                                                               |
+                   Owner Interface Identifier                  +
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|   Registration option(s)...
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 0                   1                   2                   3
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|     Type      |    Length     |    Status     |  S  |    P    |
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|D|A|R|_________________________|         IPv6 Address       ...
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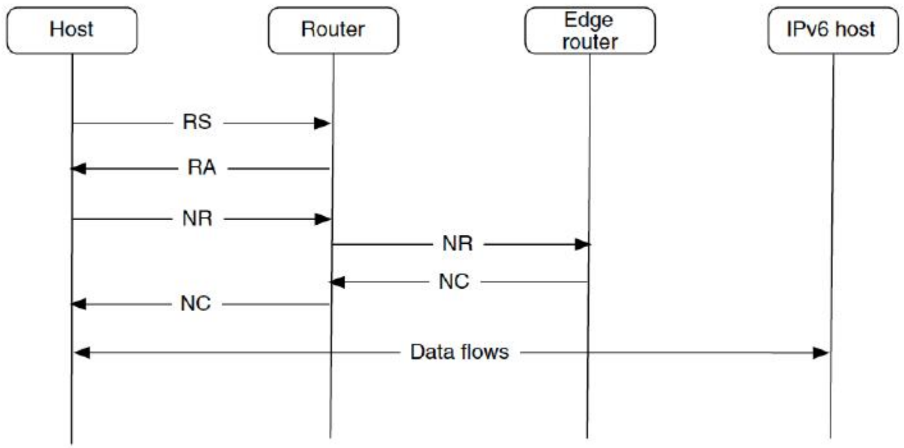
```

Bootstrapping an IoT network

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

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 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
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|       Binding Lifetime        |     Advertising Interval      |
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|  Registration option(s)...
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 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
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|     Type      |    Length     |    Status     |   S   |   P   |
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|D|A|R|_______________________|          IPv6 Address       ...
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```

Protocols for EH-WSNs

Internet of Things, a.a. 2015/2016

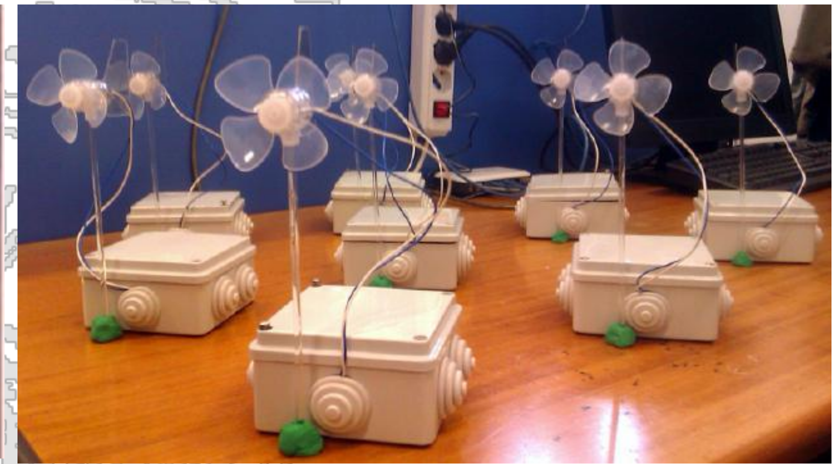
Un. of Rome "La Sapienza"

Chiara Petrioli[†]

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

EH-WNS

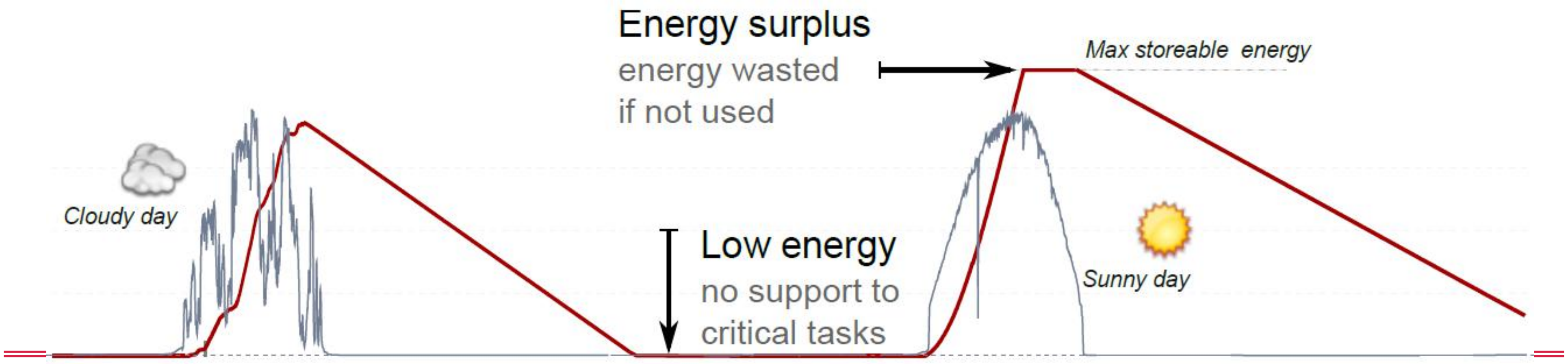





- Pose the basis for very long lasting operation
- Energy Neutral protocols have been proposed for several applications
- Changes also what a WSN can do

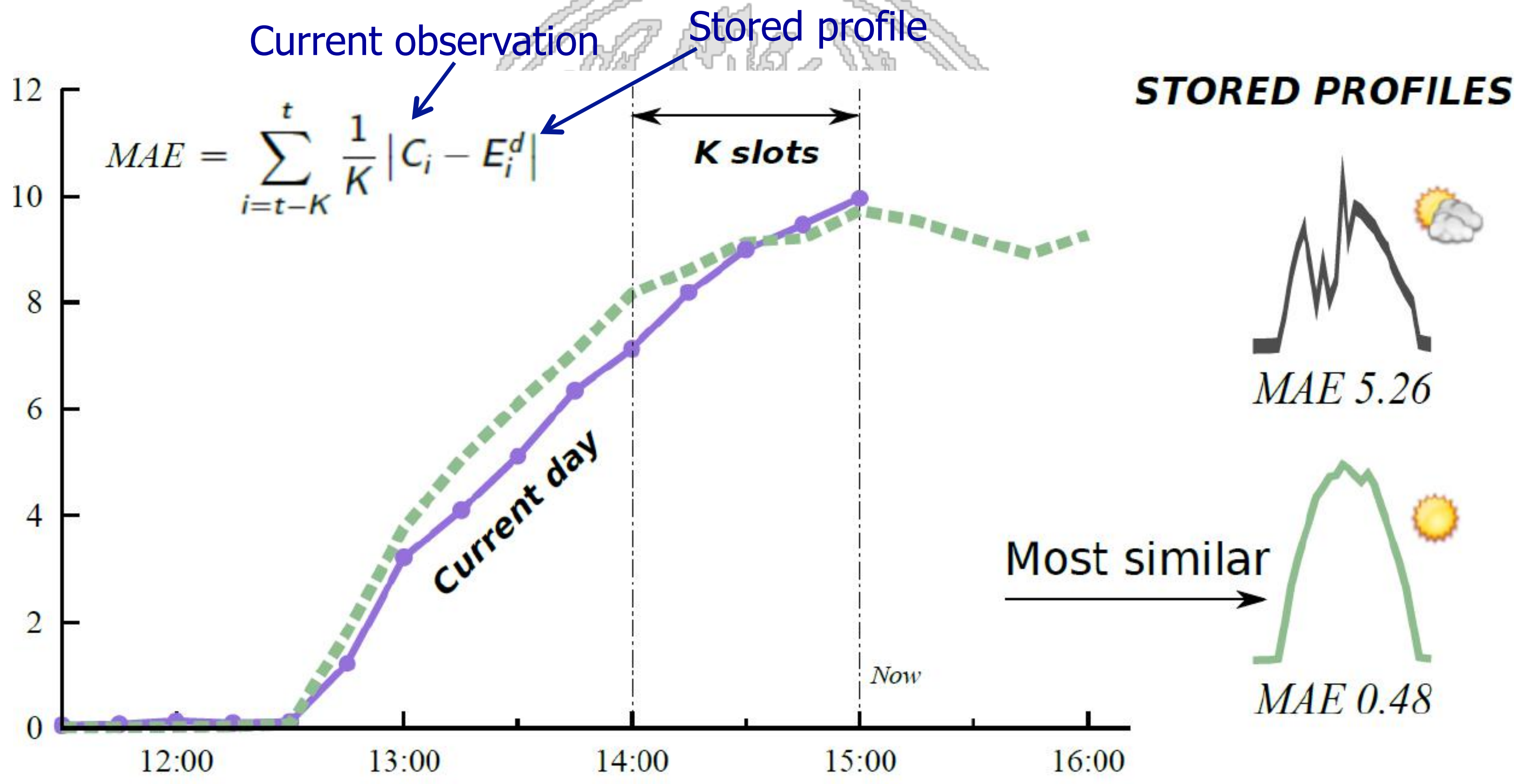
Why energy predictions?

- Energy predictions to mitigate uncertain energy availability
- 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

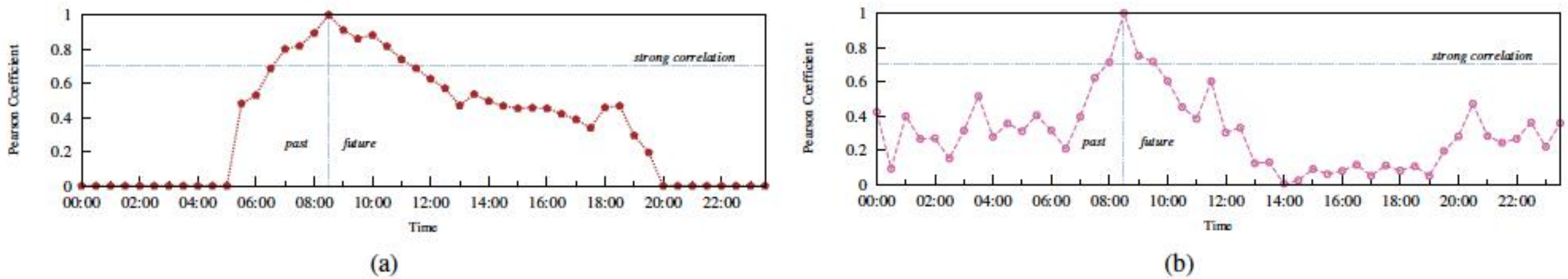


Figure 2. Pearson autocorrelation coefficient for (a) solar ORNL Dataset and (b) wind Bologna Dataset.

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

where:

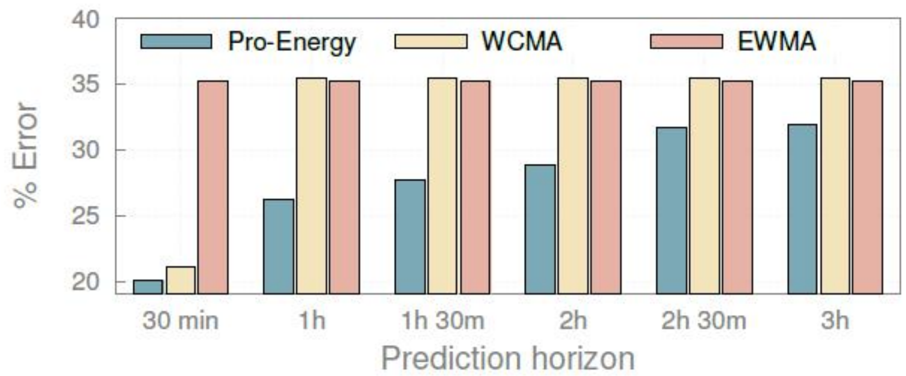
- α is the weighting factor defined in Equation (2);
- i is the i^{th} timeslot in the future, with respect to the current slot, t;
- G is the number of timeslots in the future which show a correlation above a given threshold with timeslot t;
- F is the number of future timeslots for which Pro-Energy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

Medium term energy prediction estimation

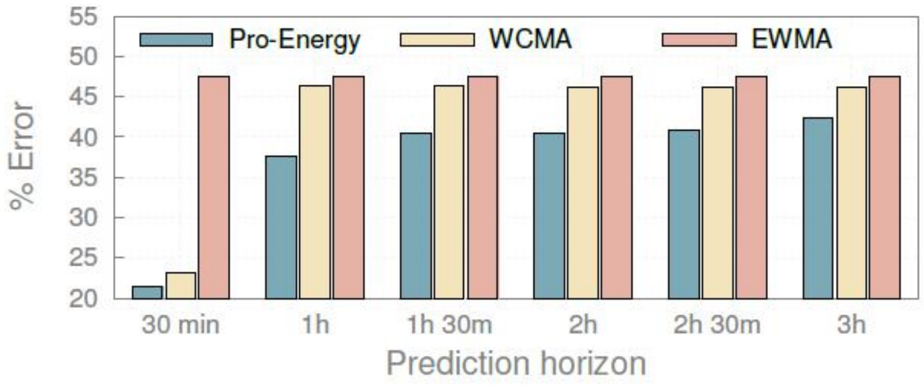
$$\hat{E}_{t+i} = \gamma_i \cdot C_t + (1 - \gamma_i) \cdot E^d_{t+i}$$

Pro-Energy accuracy

Solar



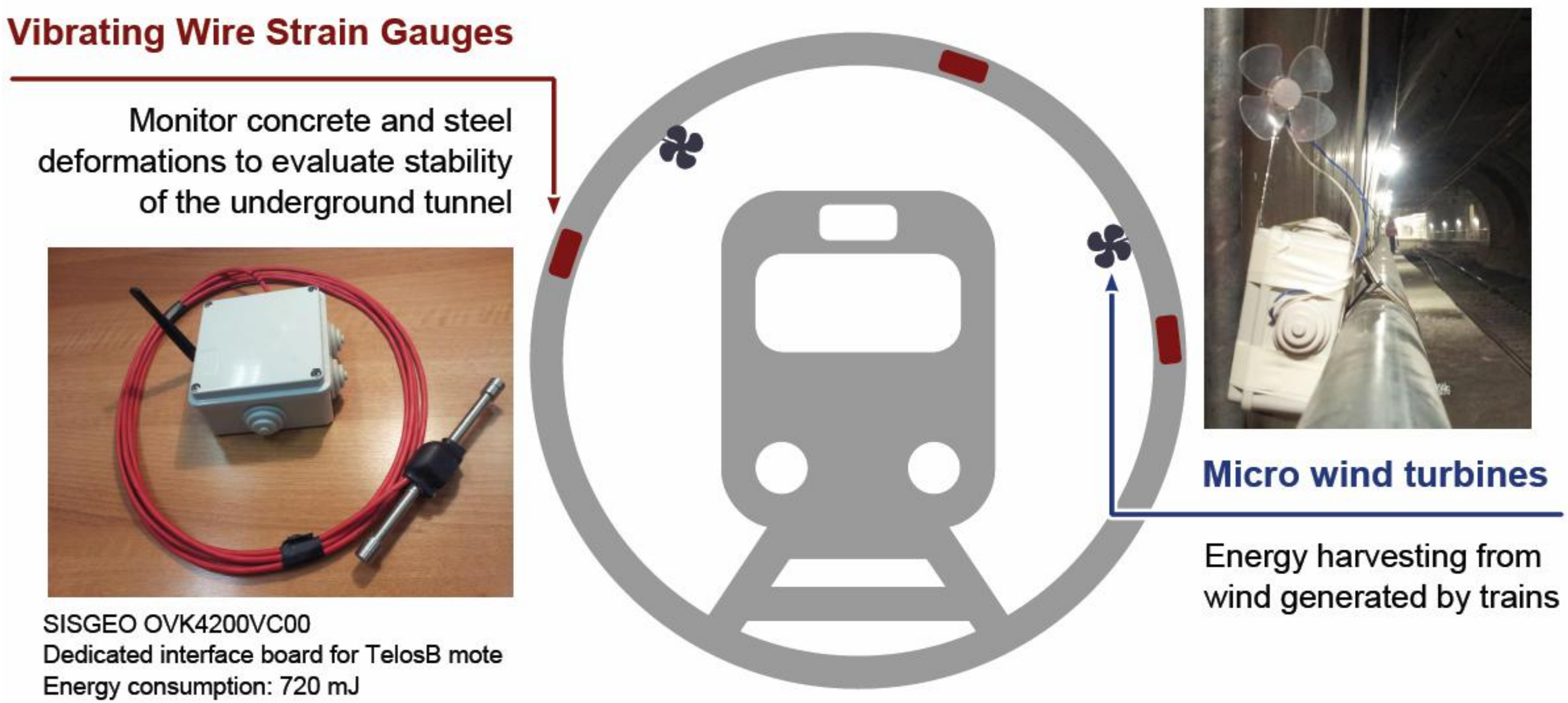
Wind



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

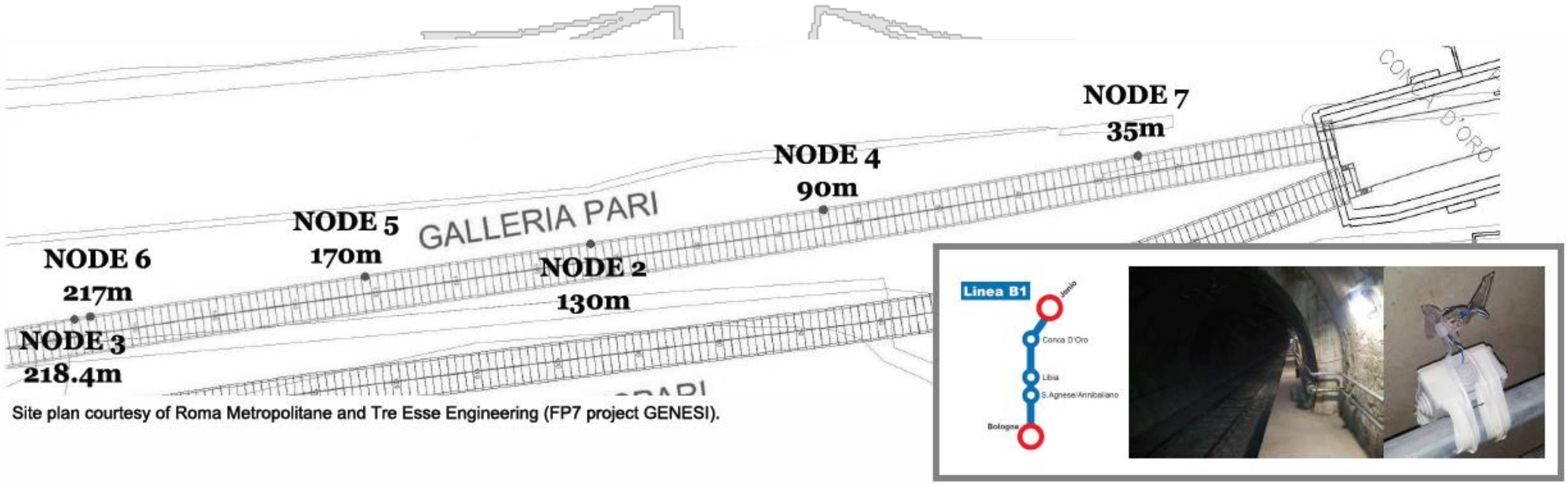
Rome underground testbed



Why air-flow energy harvesting?

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

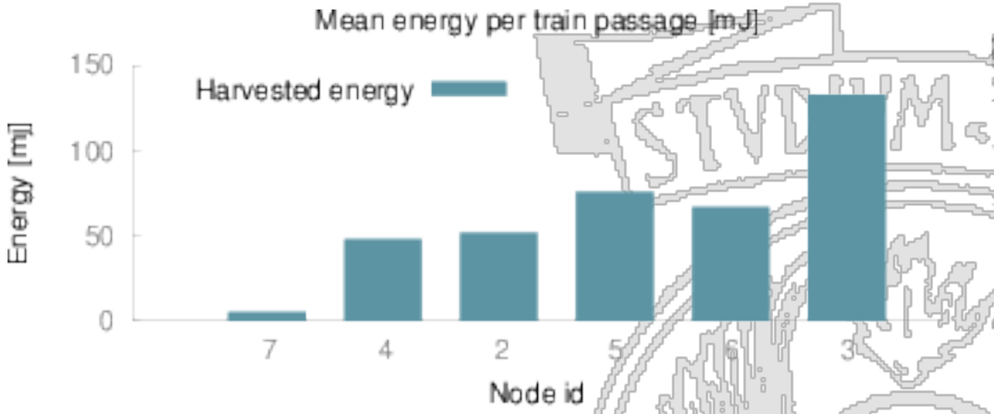
In-field air-flow data collection



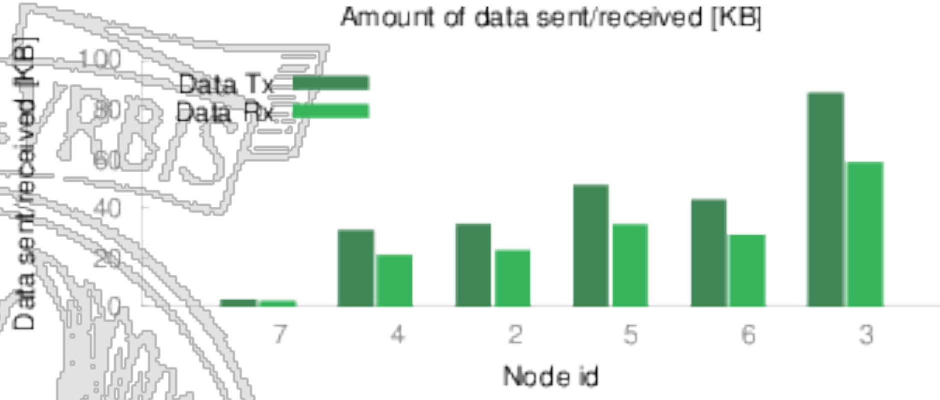
Site plan courtesy of Roma Metropolitane and Tre Esse Engineering (FP7 project GENESI).

220 meter of instrumented tunnel
6 energy-harvesting nodes
33 days of data collection

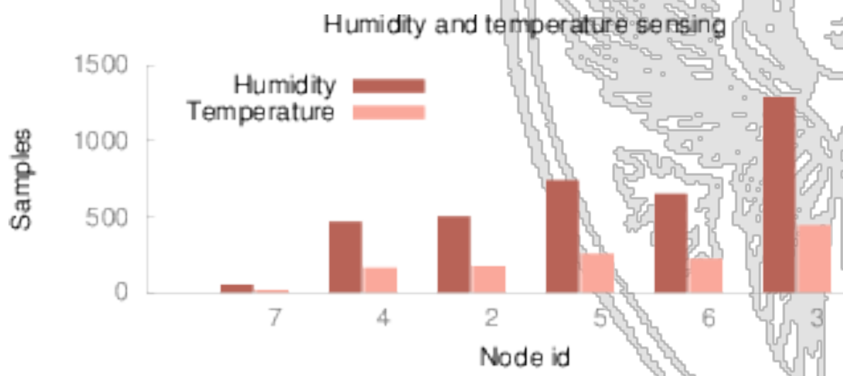
Feasibility study



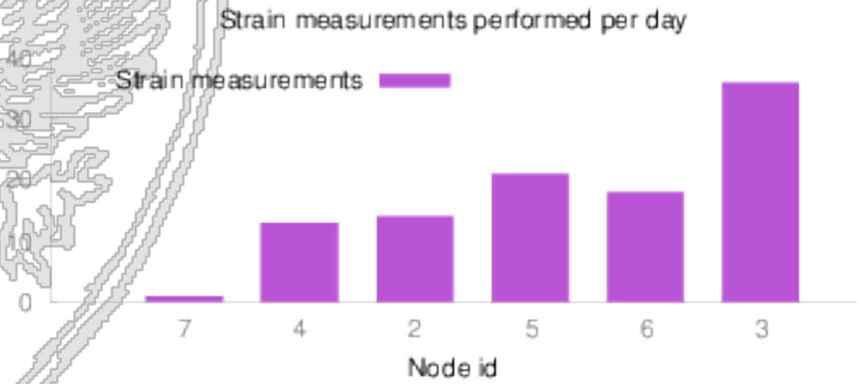
Up to 133 mJ harvested per train passage



Transmit/receive tens of KB



Collect hundreds of humidity and temperature samples

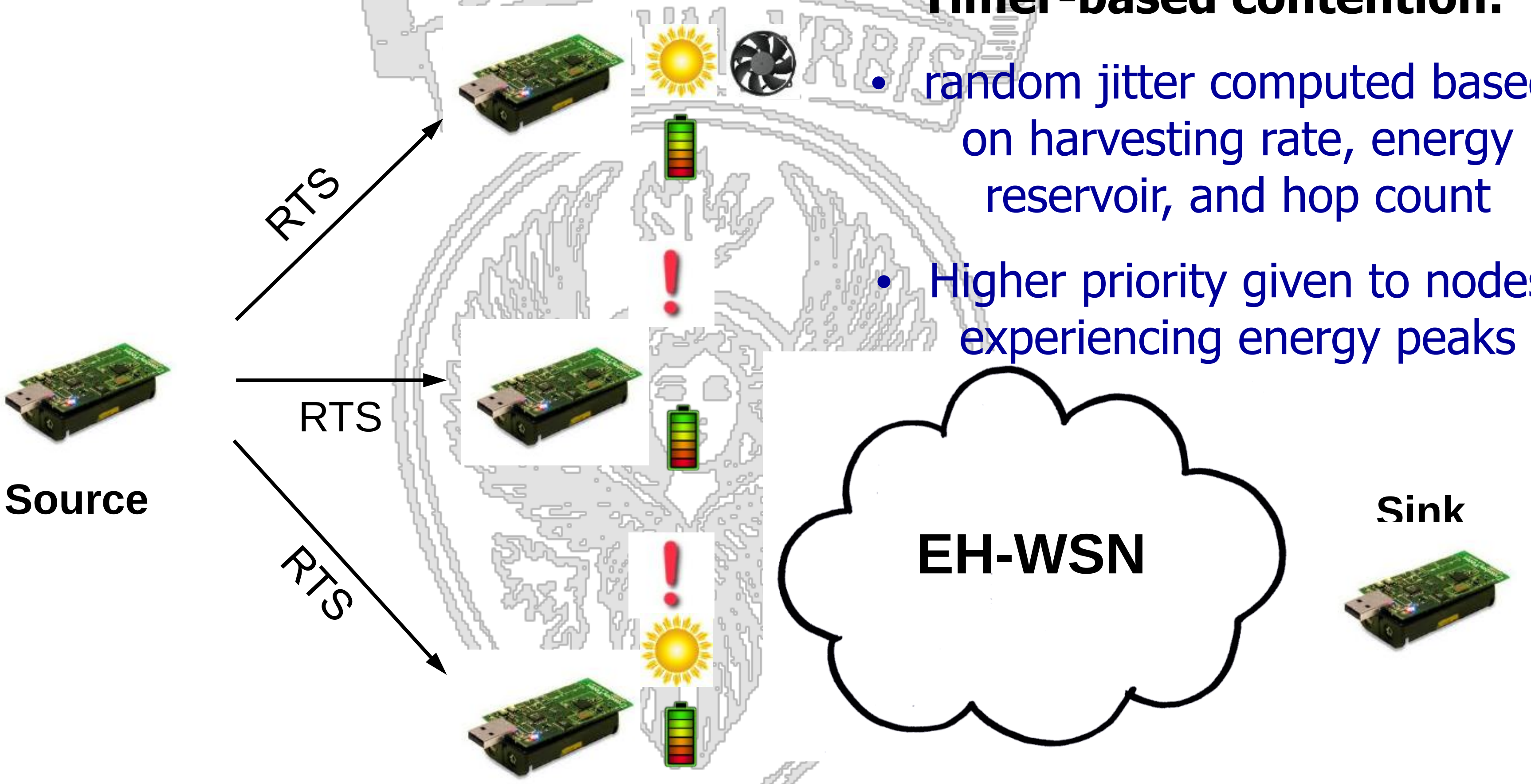


Up to 36 strain measurements per day

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



Harvesting-aware routing

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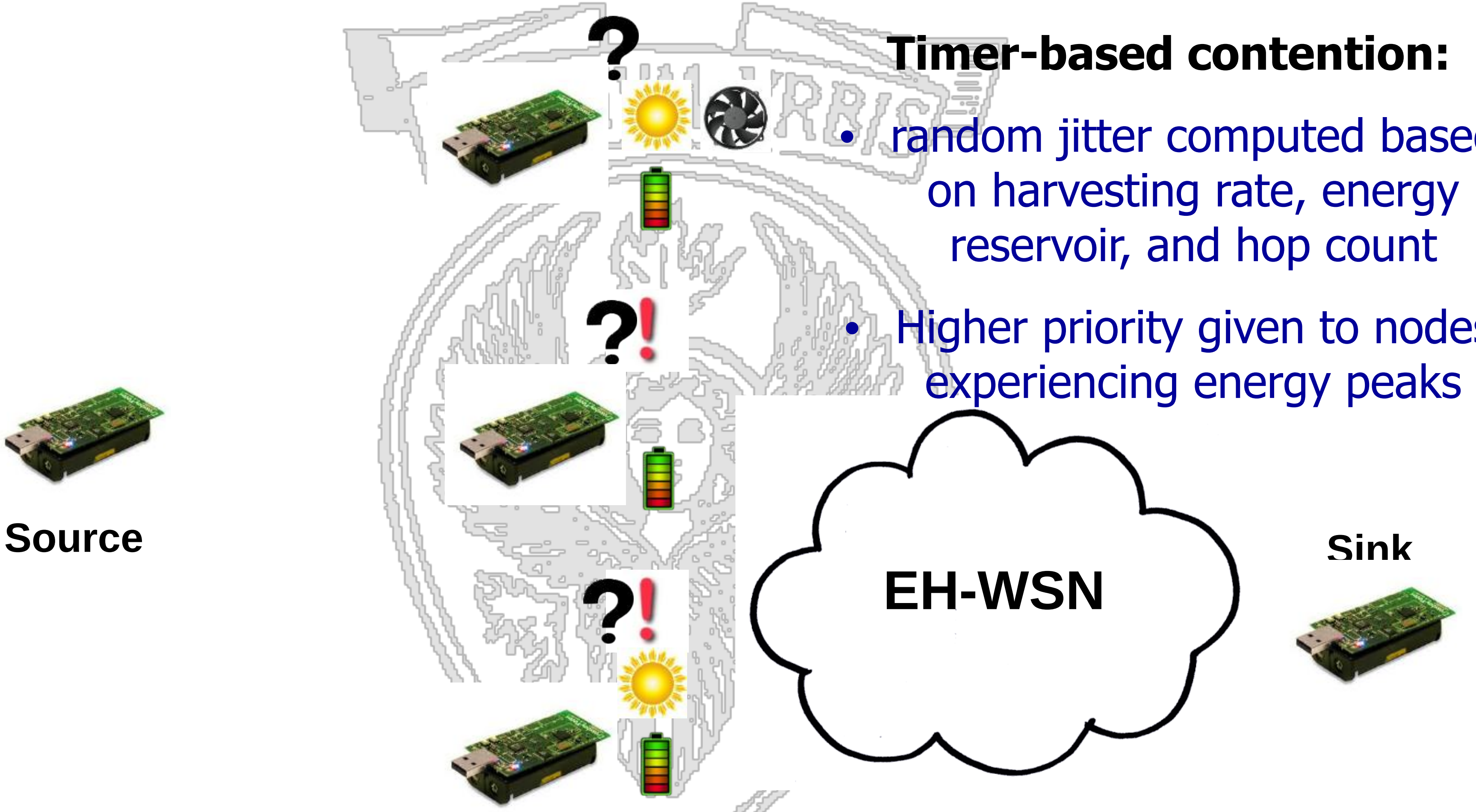

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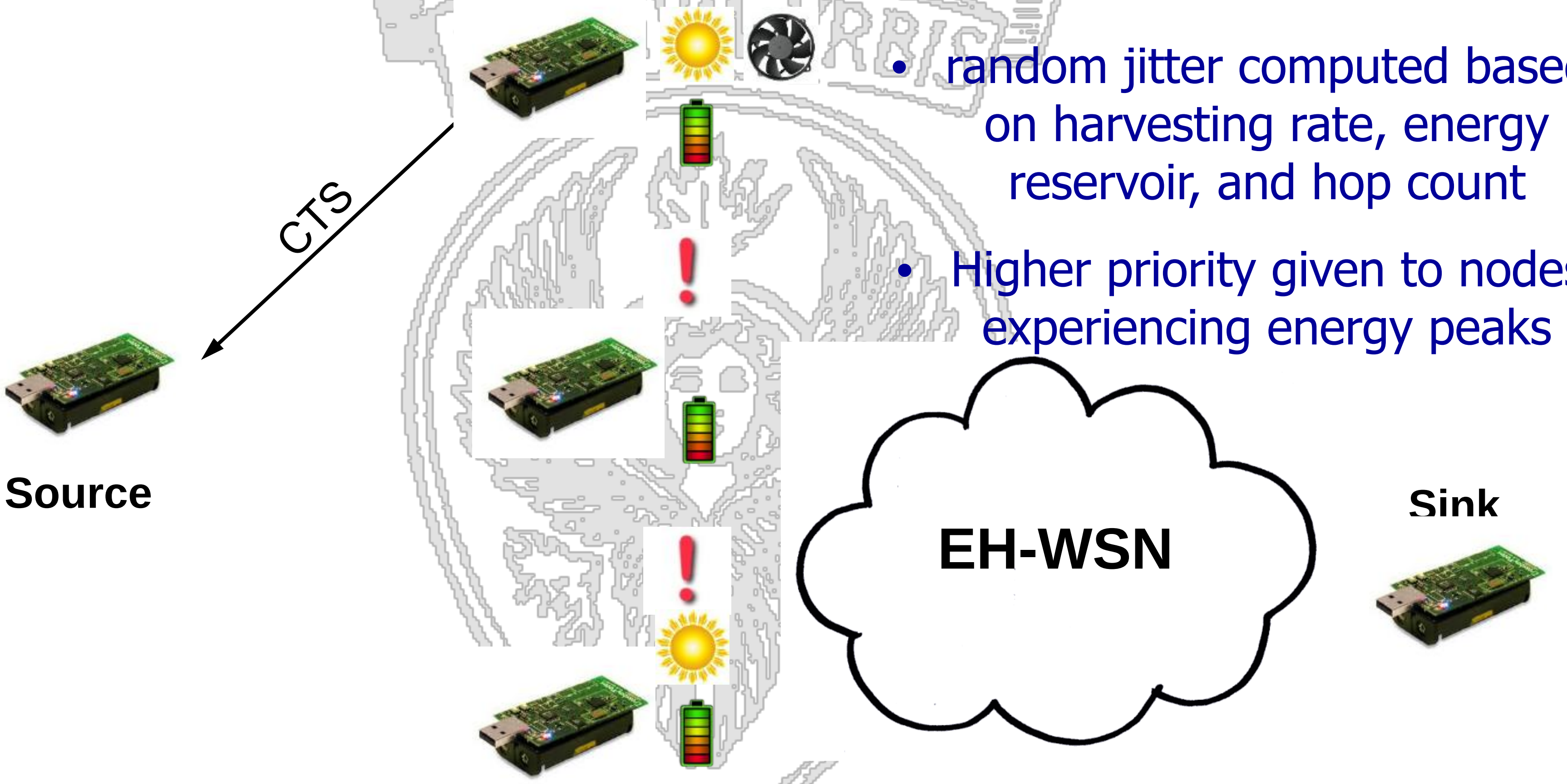

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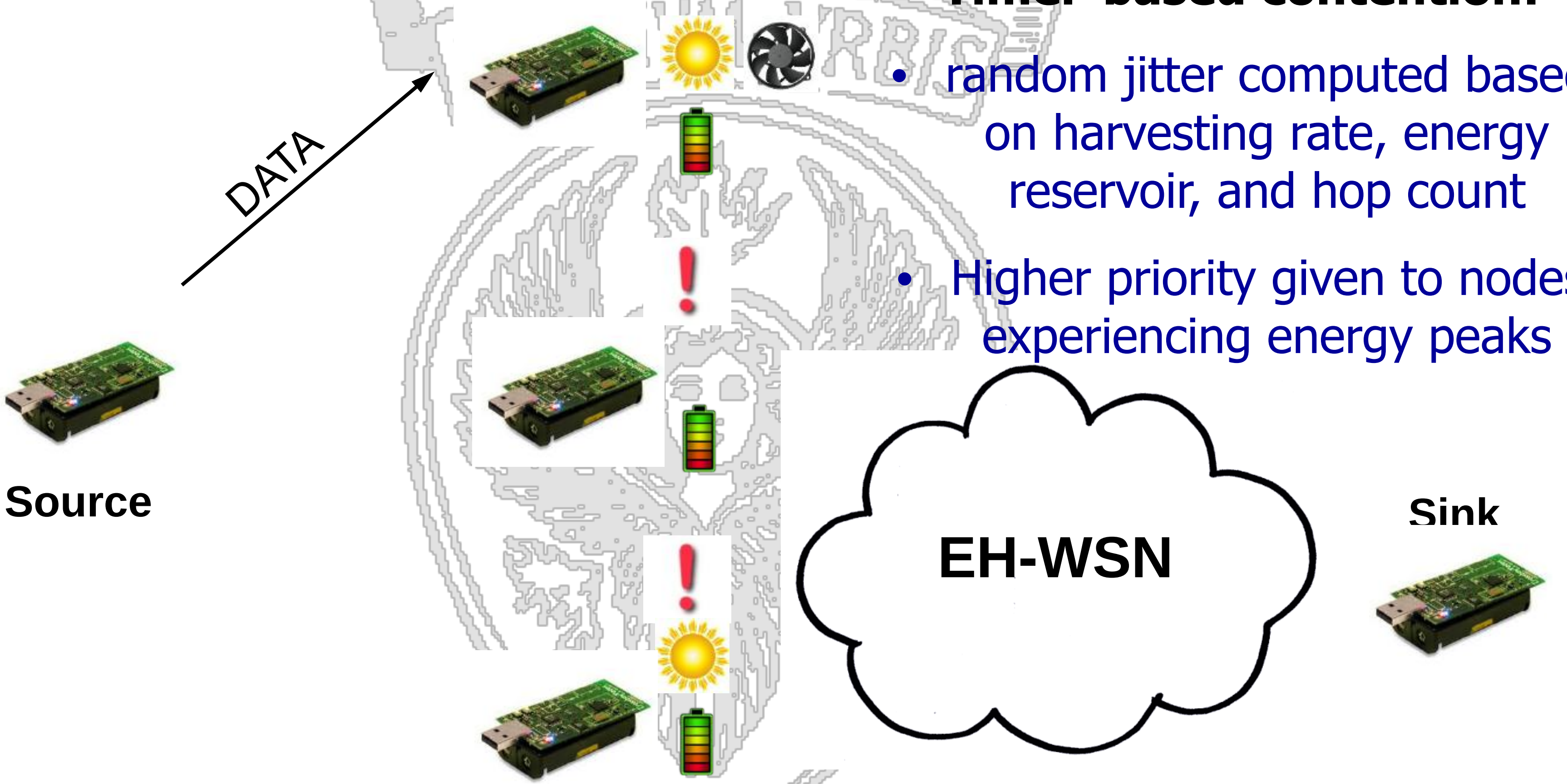
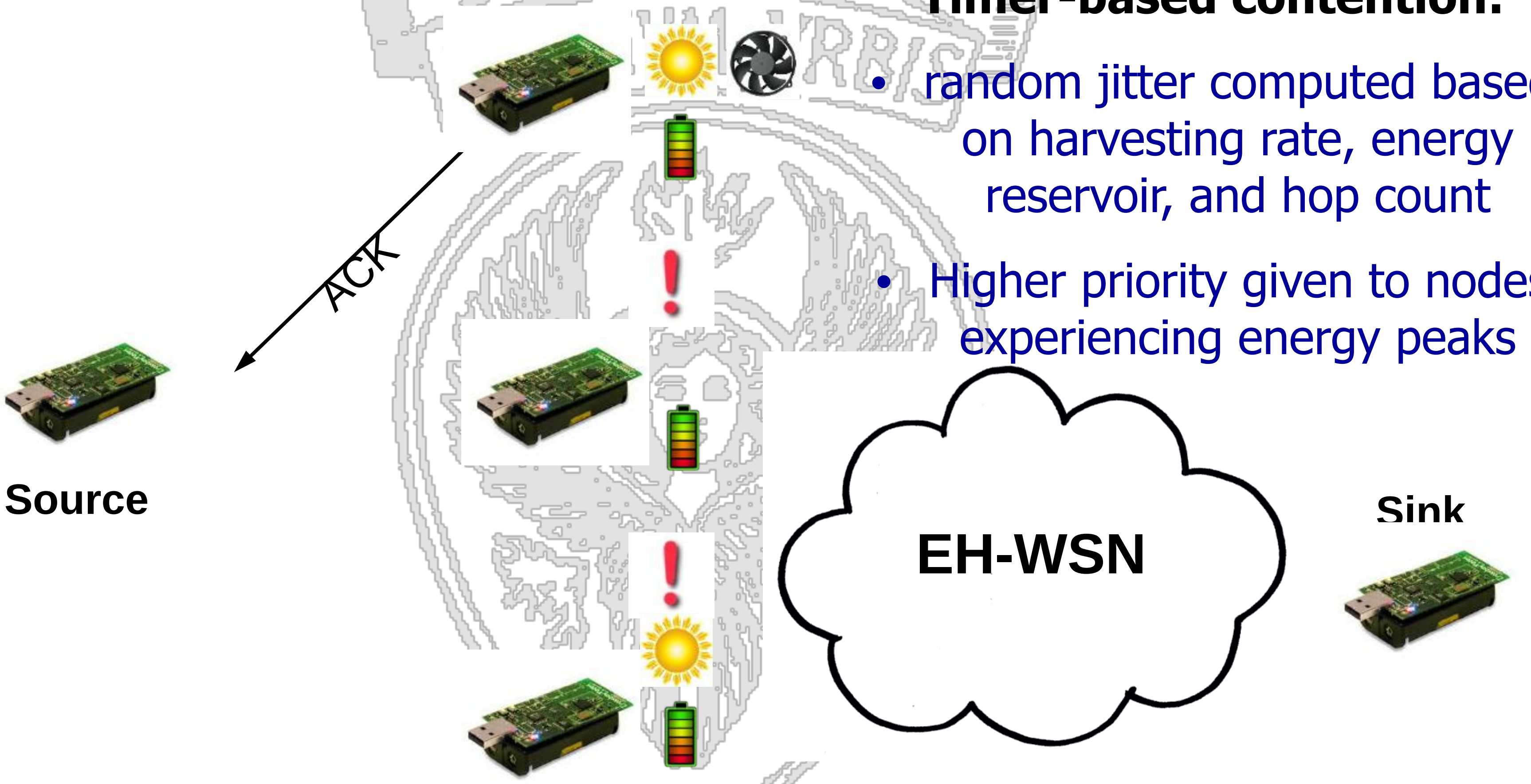


Harvesting-aware routing



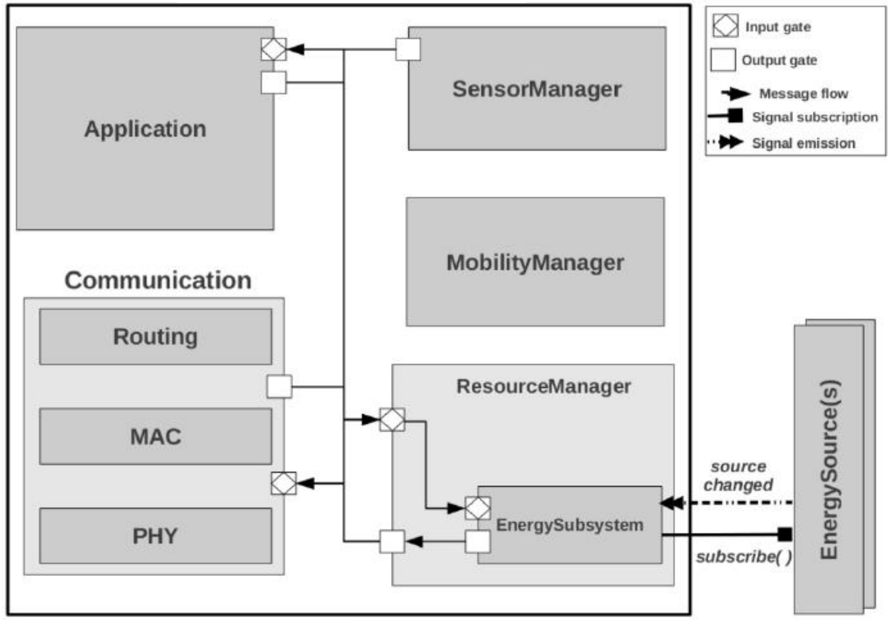
Timer-based contention:

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

GreenCastalia: Motivation

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

Sensor node



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

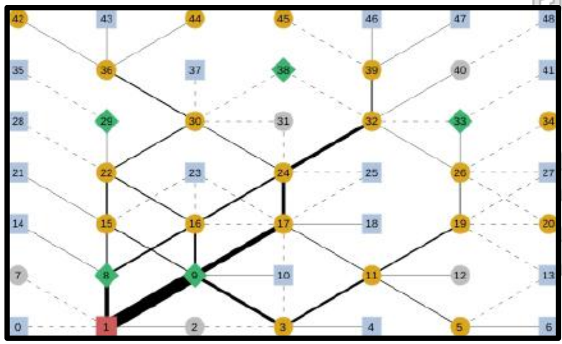
SAPIENZA
UNIVERSITÀ DI ROMA

Harvesting-aware routing: Results

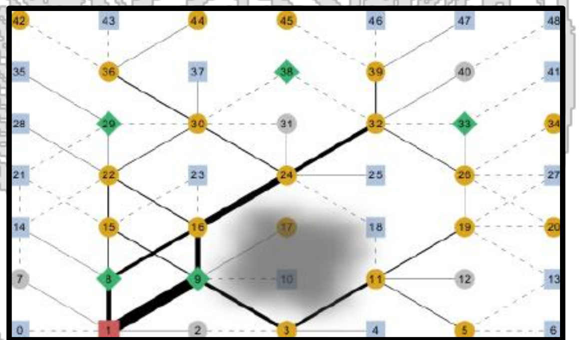
Simulation settings

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

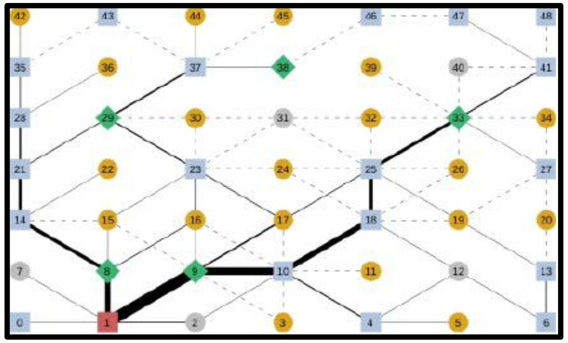
11am



5pm with shadow zone



8pm

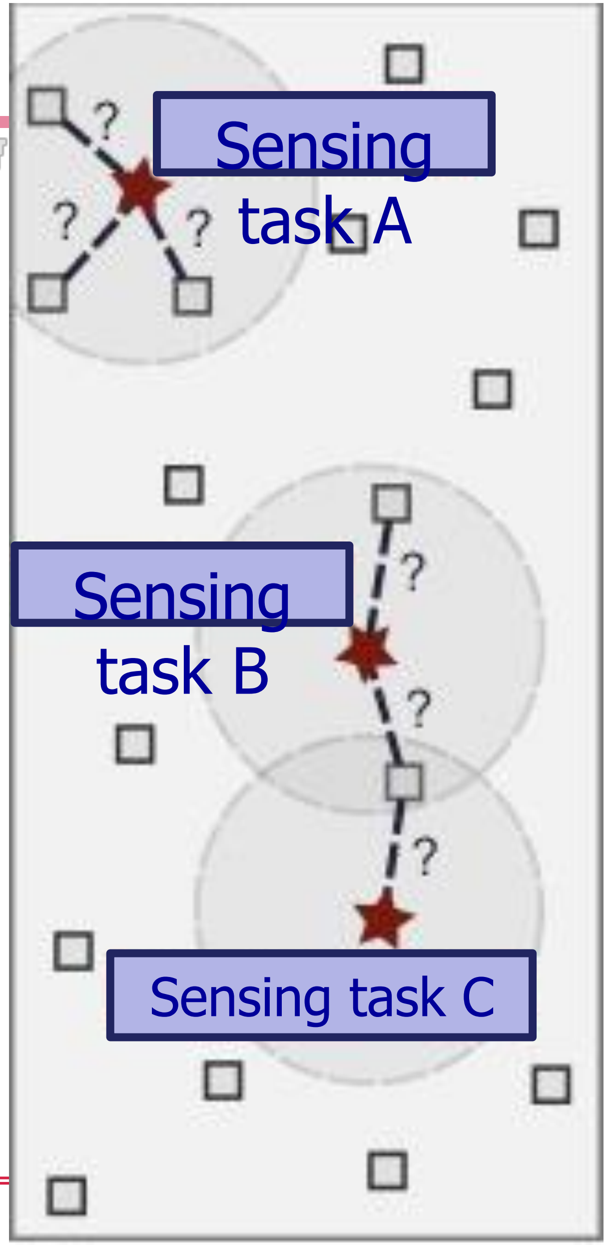


Self-adaptive behaviour: nodes experiencing energy peaks are selected with higher priority as next hop relays

Task allocation

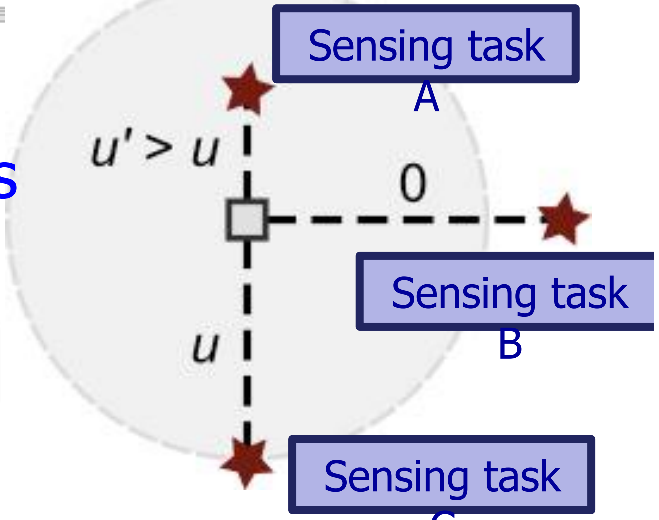
- Sensing tasks (missions) arrive in the network dynamically over time at different locations
- Multiple missions active at the same time, competing for the sensing resources of the network

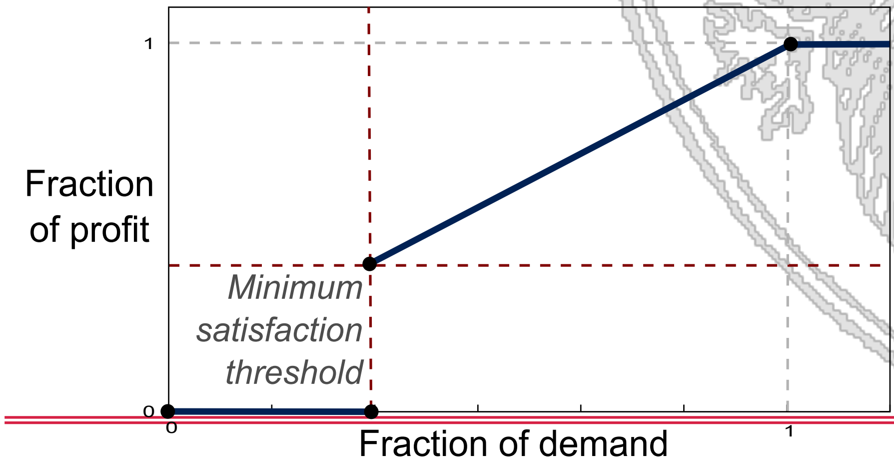
Decide which sensor(s) should be assigned to each mission



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

3. Target network lifetime

Classify missions

4. Current energy level of the node (fuel cell + supercap)
5. Energetic cost of the mission
6. 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

A new mission arrives → check energy requirements and energy availability

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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

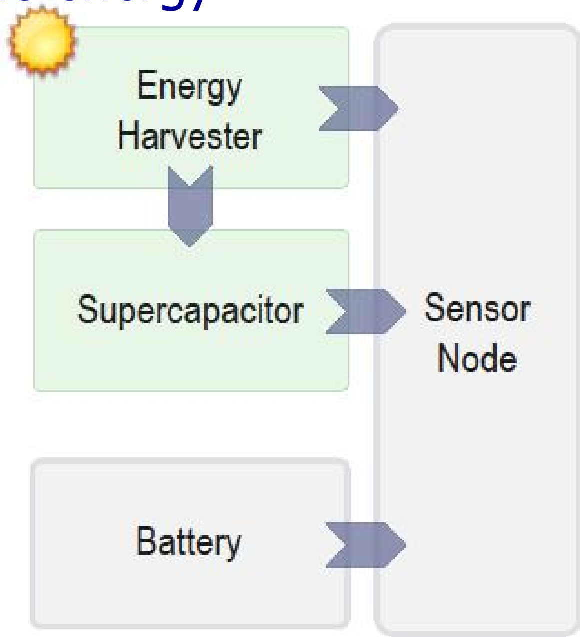
A **decentralized** harvesting-aware heuristic

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

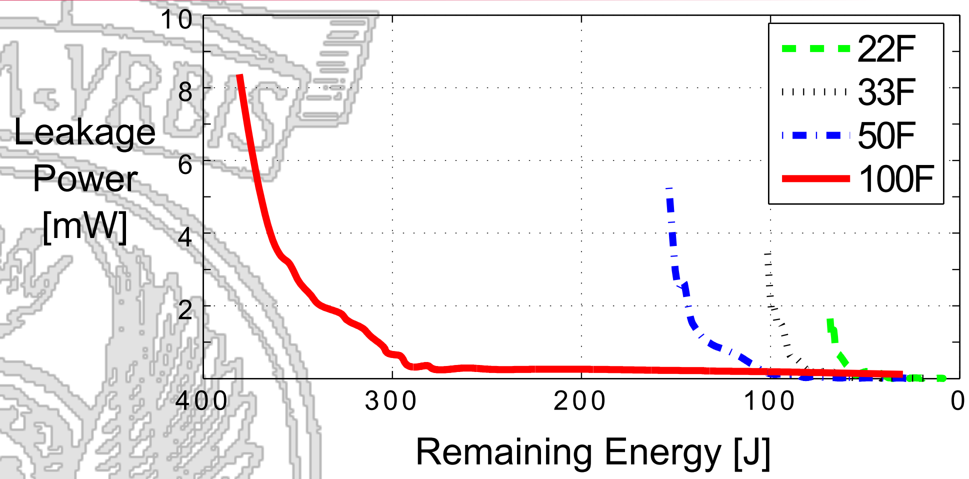
1. **Free:** fully sustained by harvesting
2. **Recoverable:** sustained by supercapacitor and recovered before next mission
3. **Capacitor-sustainable:** sustained by supercapacitor
4. **Battery-required:** sustained by battery



Modeling real harvesting systems

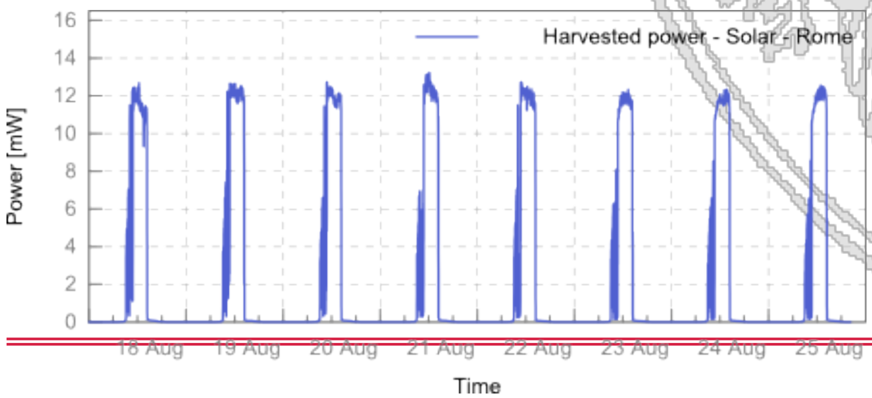
Non-ideal supercapacitors

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

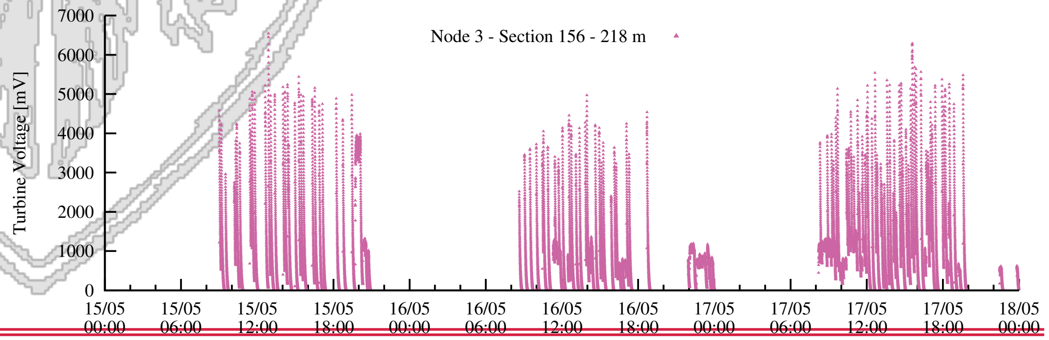


Real-life energy traces

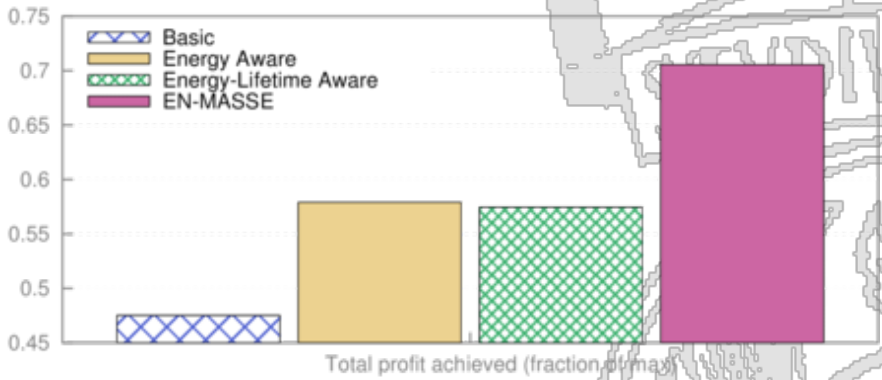
Photovoltaic cells

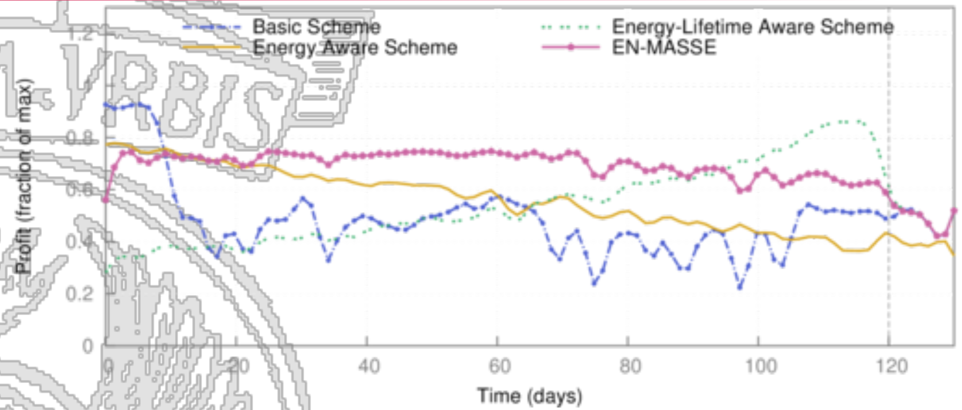


Wind micro-turbines



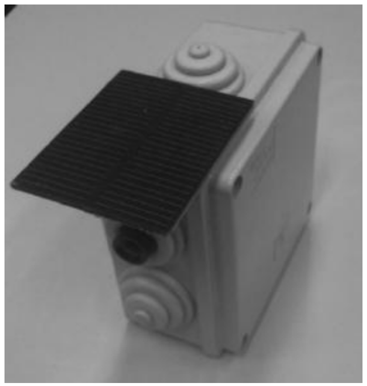
Performance evaluation

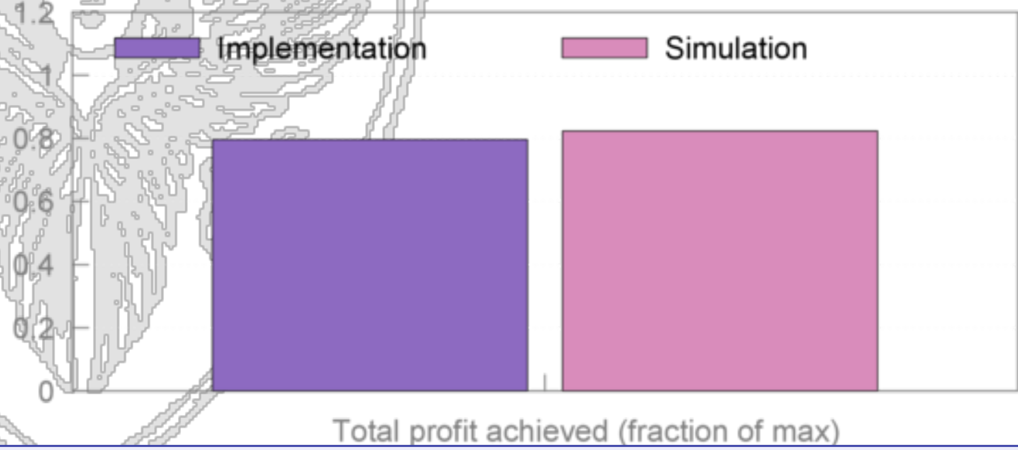




Profit: up to 60% higher than SoA

<u>Stable</u> profit: 70-80% of maximum





In-field testbed validation

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