MAC Protocols for sensing systems

Internet of Things a.a. 2020/2021

Un. of Rome "La Sapienza"

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Standard-like routing Protocols for WSNs

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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

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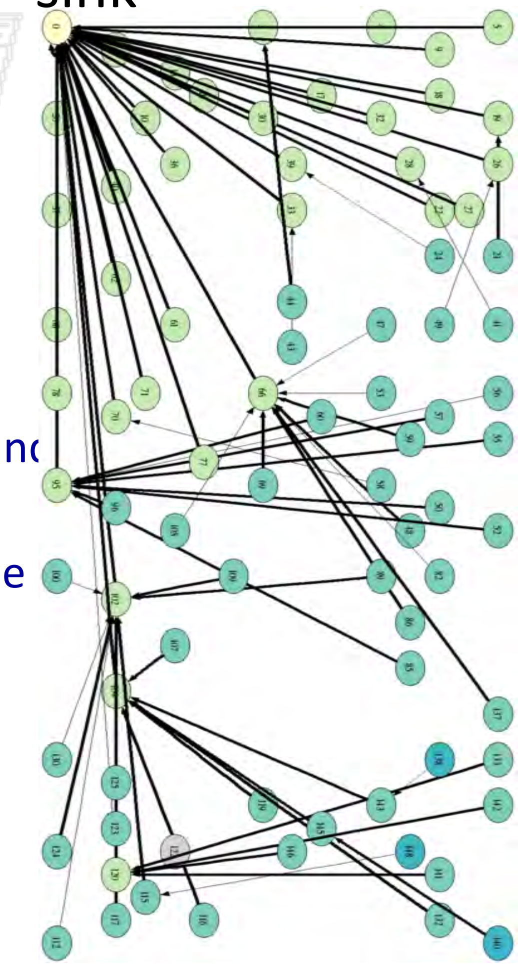
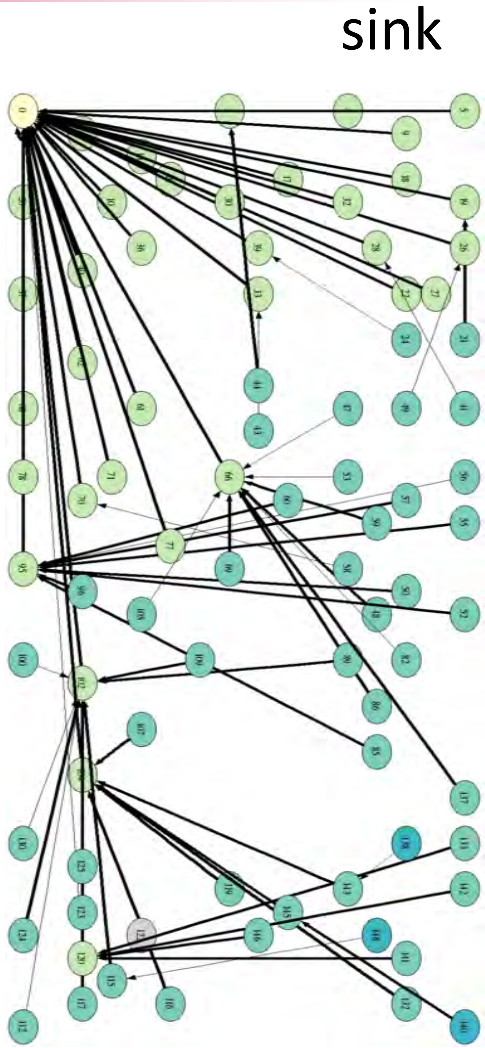
Collection

sink



- 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

Congested bit

- ETX = Expected Number of Tra
- Comput[...]orma past by beacon and data packe

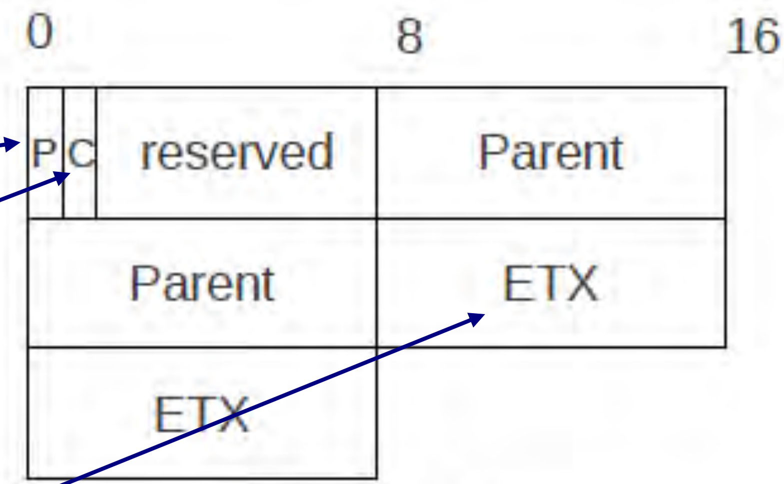
$$Q_u = \frac{n_u}{n_a}.$$

Routing cost

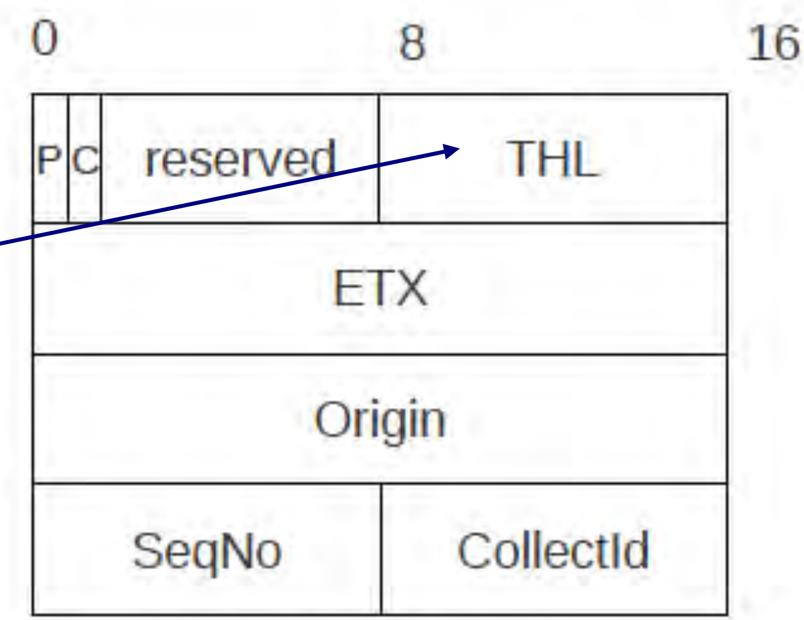
- ETX_{mhp} via a given neighbor co ETX_{loc} and of the estimated ETX at that neigh

Time has lived

Parent selected only amon



a. CTP Routing Frame



b. CTP Data Frame

Common Architecture

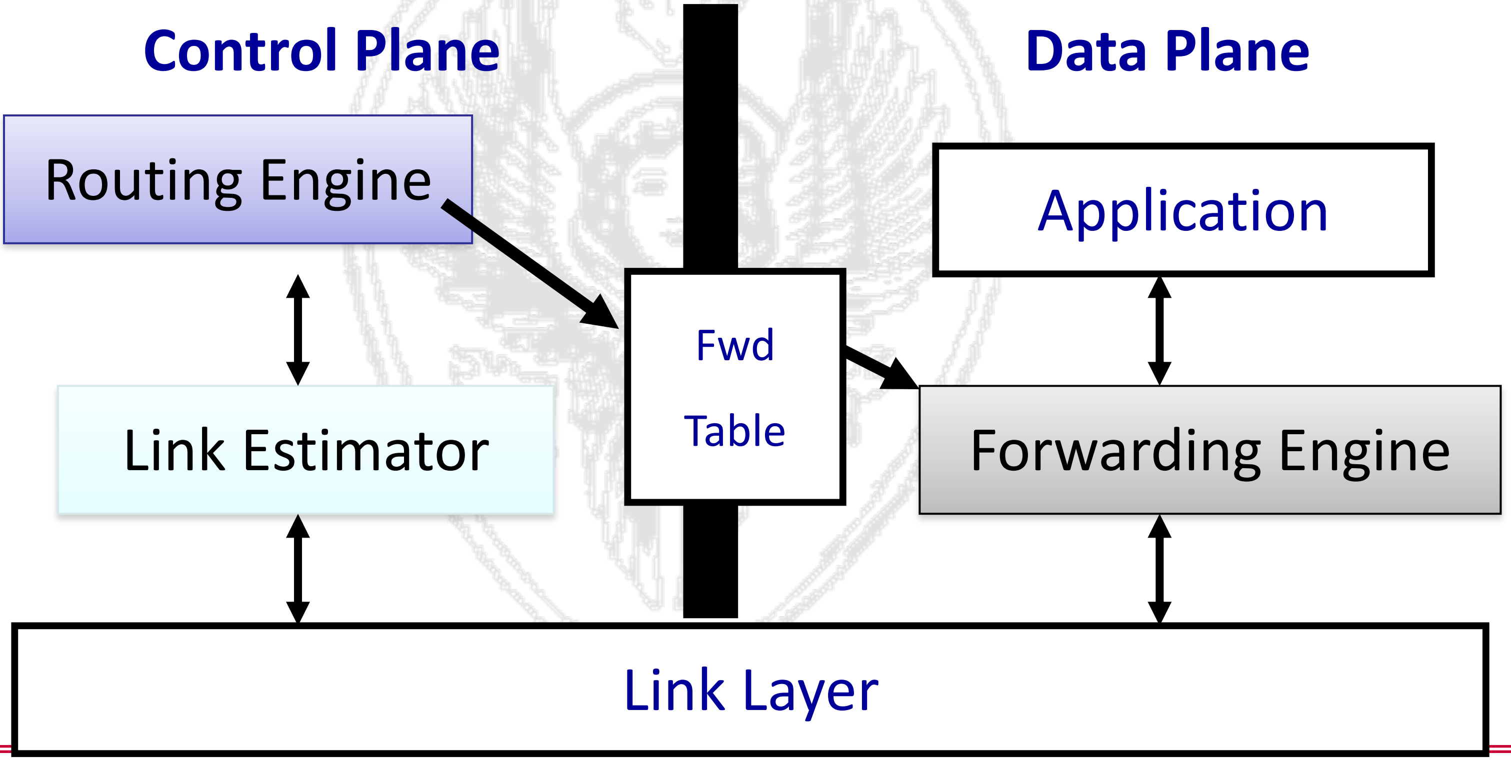
Sending and receiving beacons

for route construction and maintenance

Creating and updating the routing table

Perform forwarding

Detect and Repair Loops, filter duplicate packets



Paren

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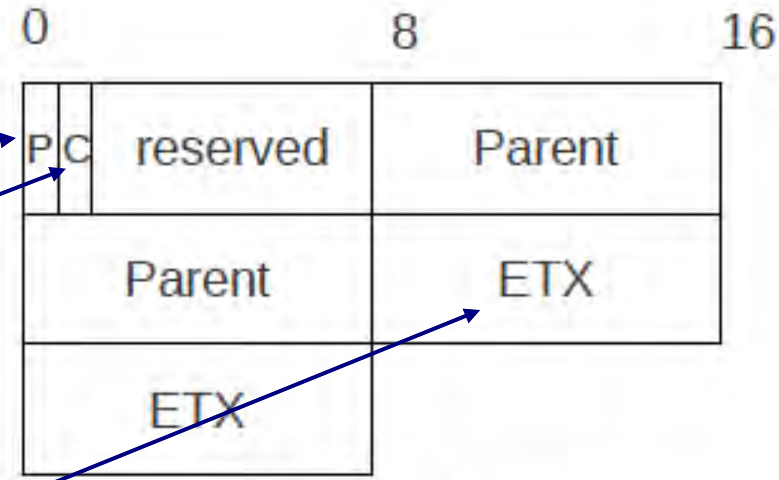

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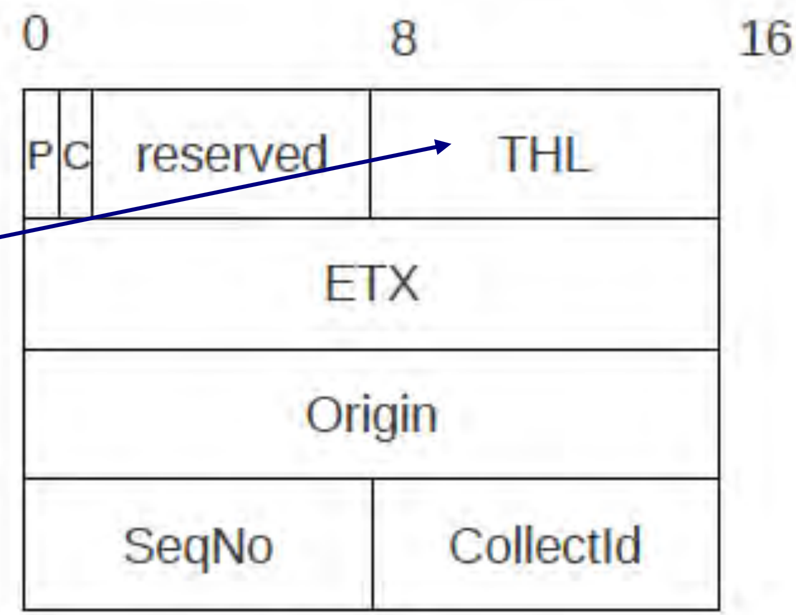
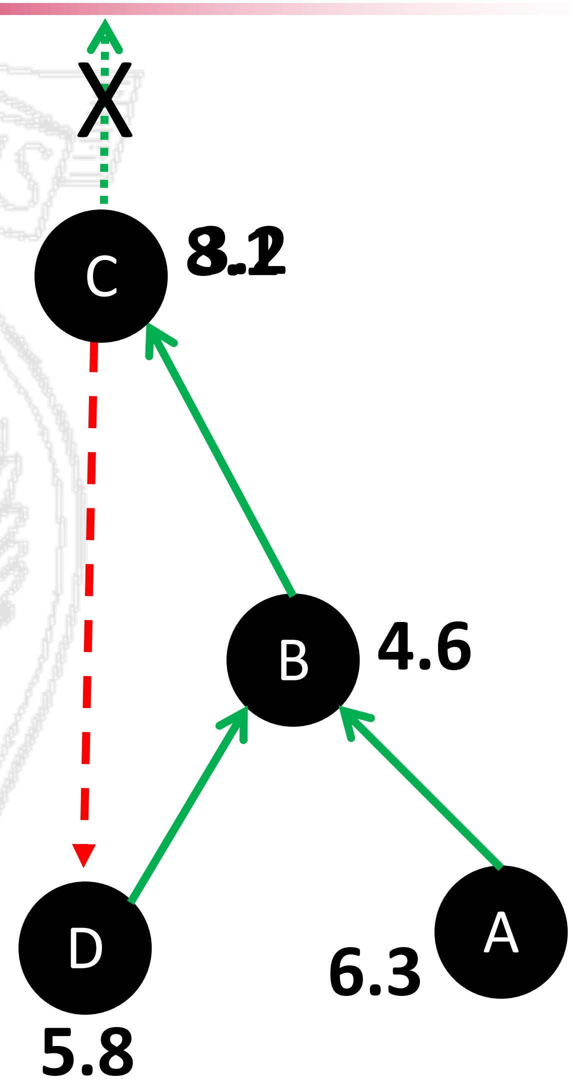


b. CTP Data Frame

Routing Loops

– Cost does not decrease

Parent selected as the neighbor with lowest cost

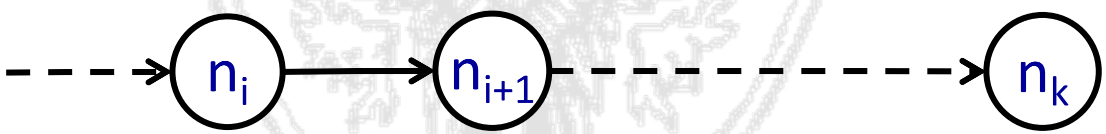


Routing Consistency

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

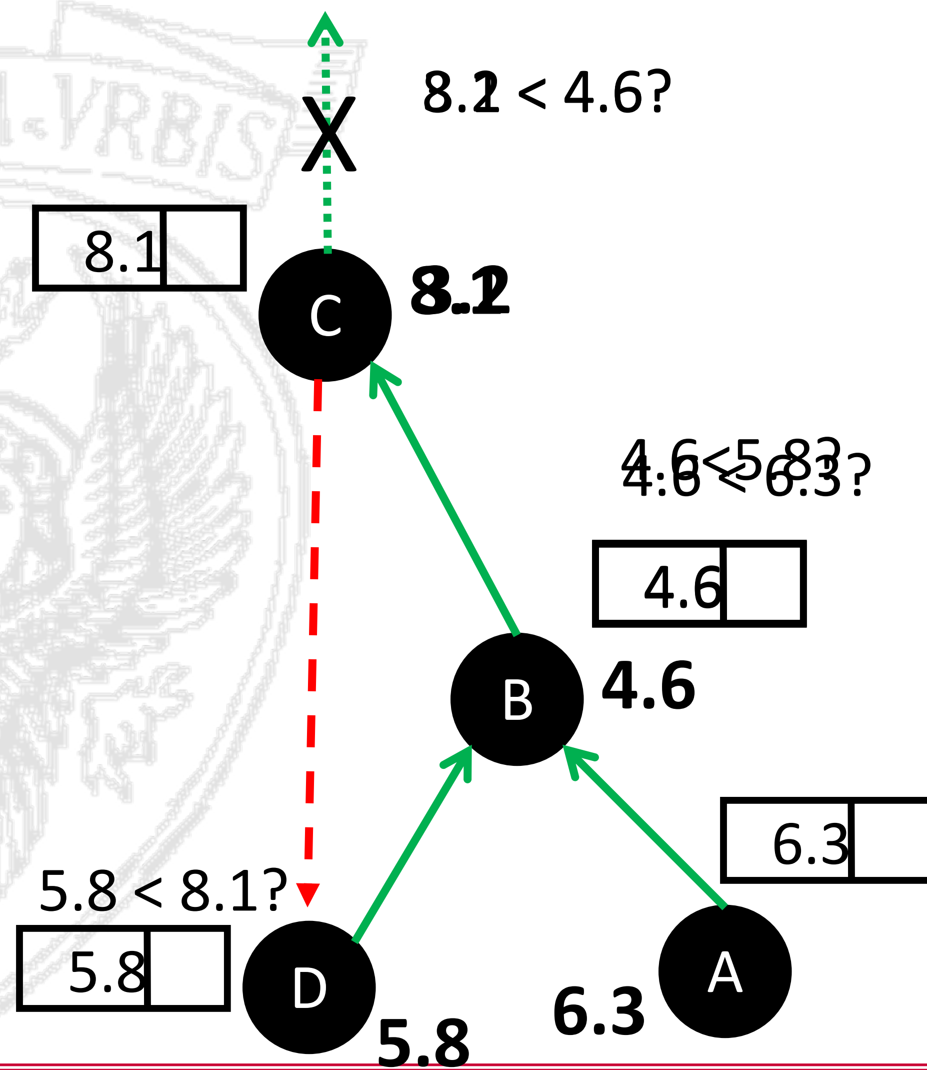
$$\forall i \in \{0, k-1\},\ ETX(n_i) > ETX(n_{i+1})$$

- Inconsistency due to stale state



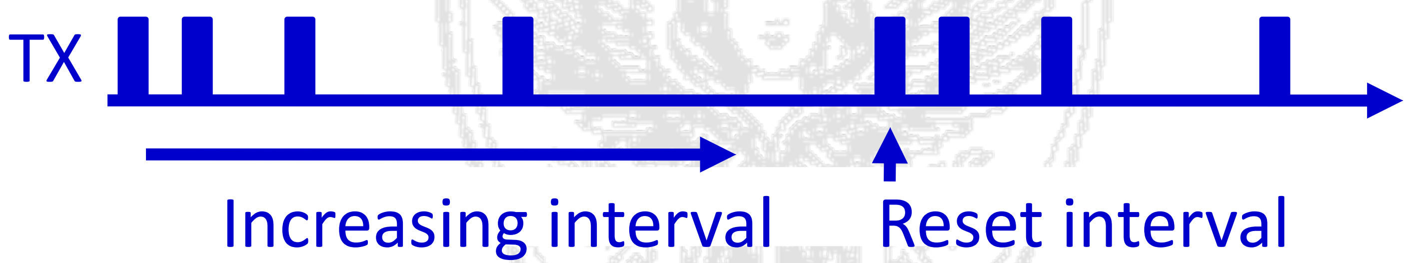
Detecting Routing Loops

- 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

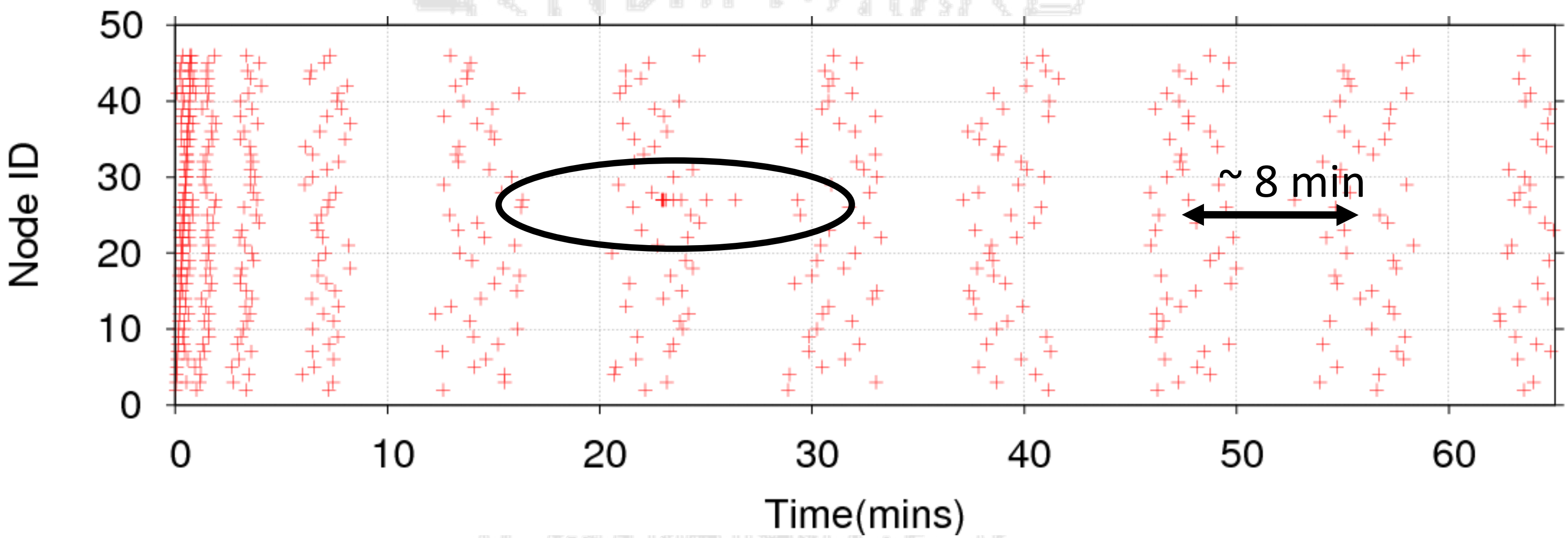
- Extend Trickle to time routing beacons
- Reset the interval
  - ✓ ETX(receiver) >= ETX(sender)
  - ✓ Significant decrease in gradient
  - ✓ "Pull" bit



Control propagation rate

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

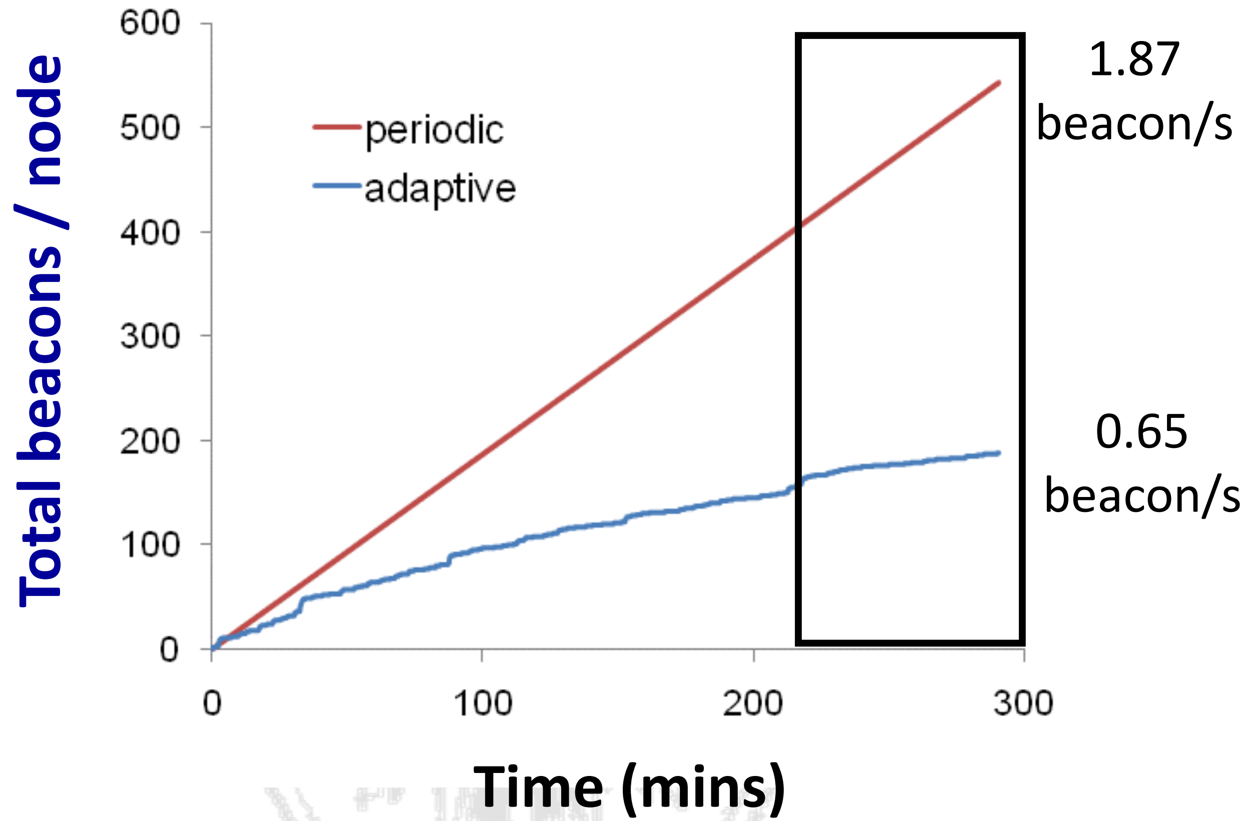
Adaptive Beacon Timing



Tutornet

Infrequent beacons in the long run

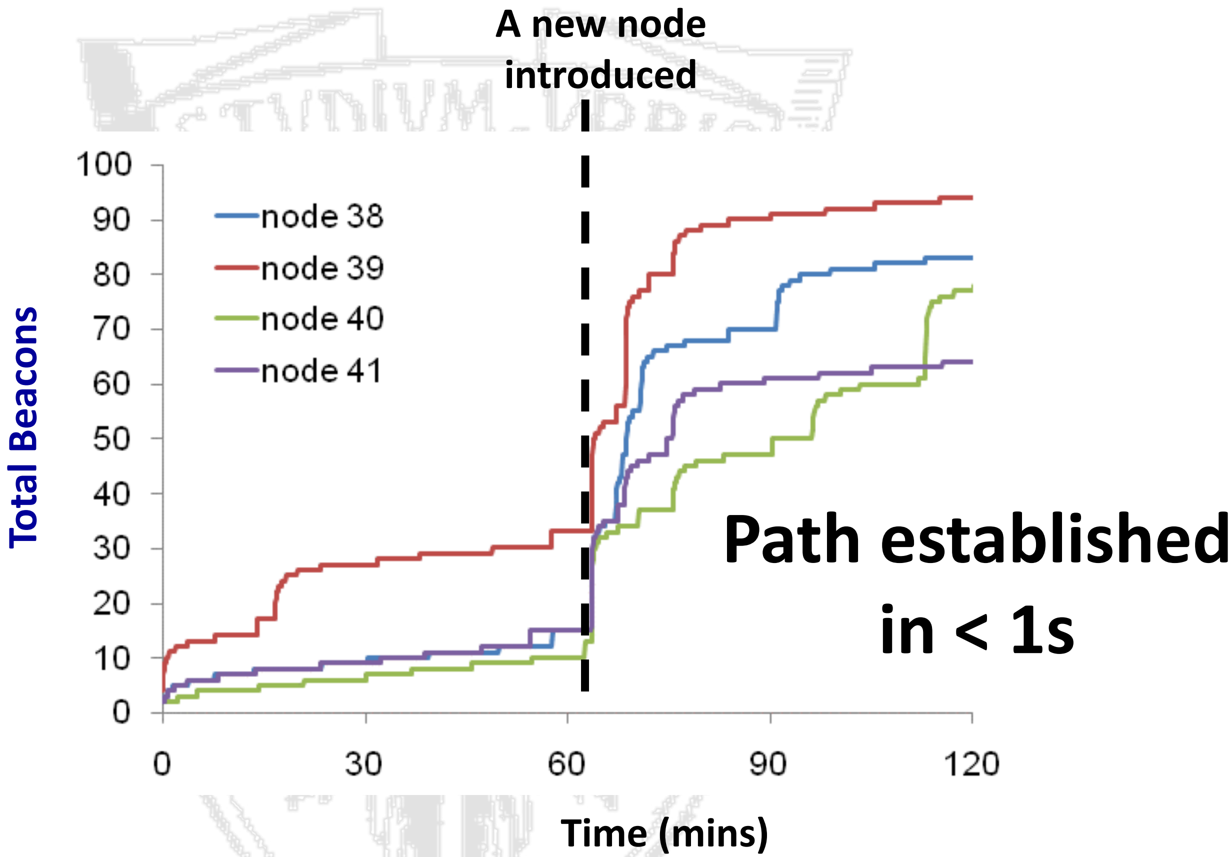
Adaptive vs Periodic Beacons



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

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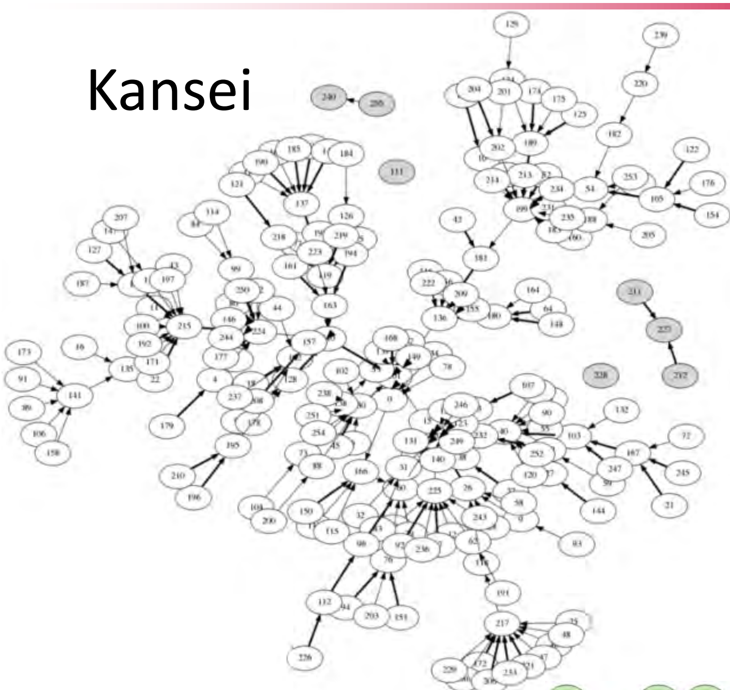
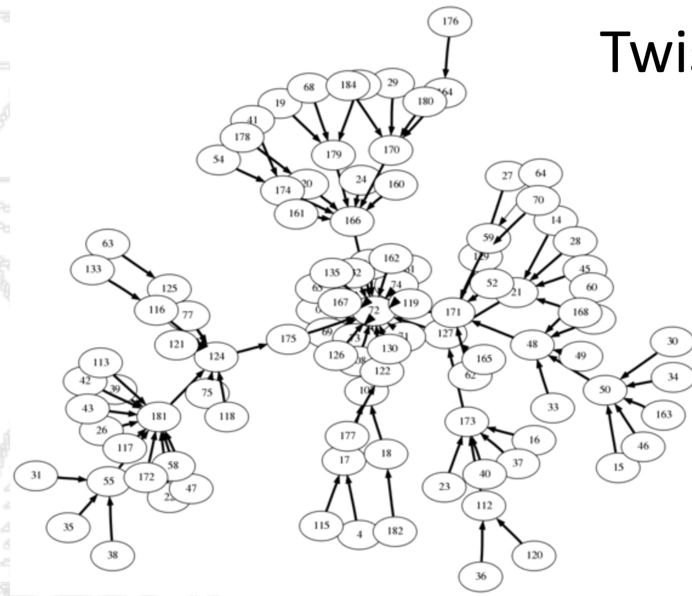
CTP Noe Trees

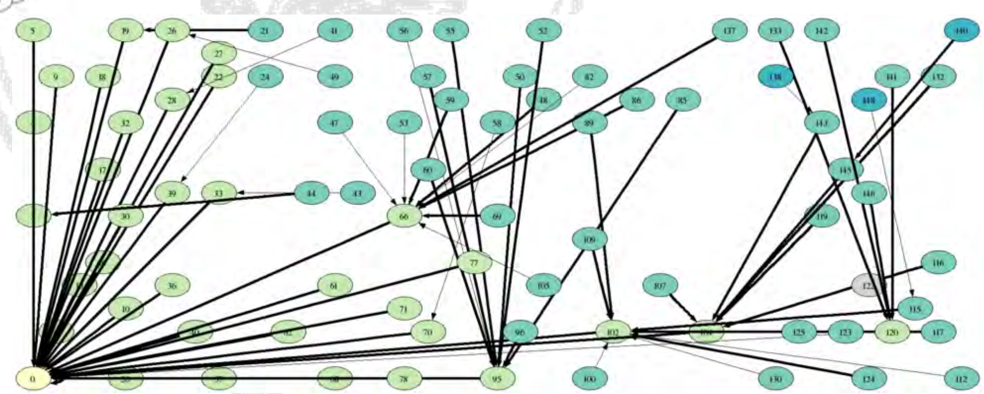
Kansei

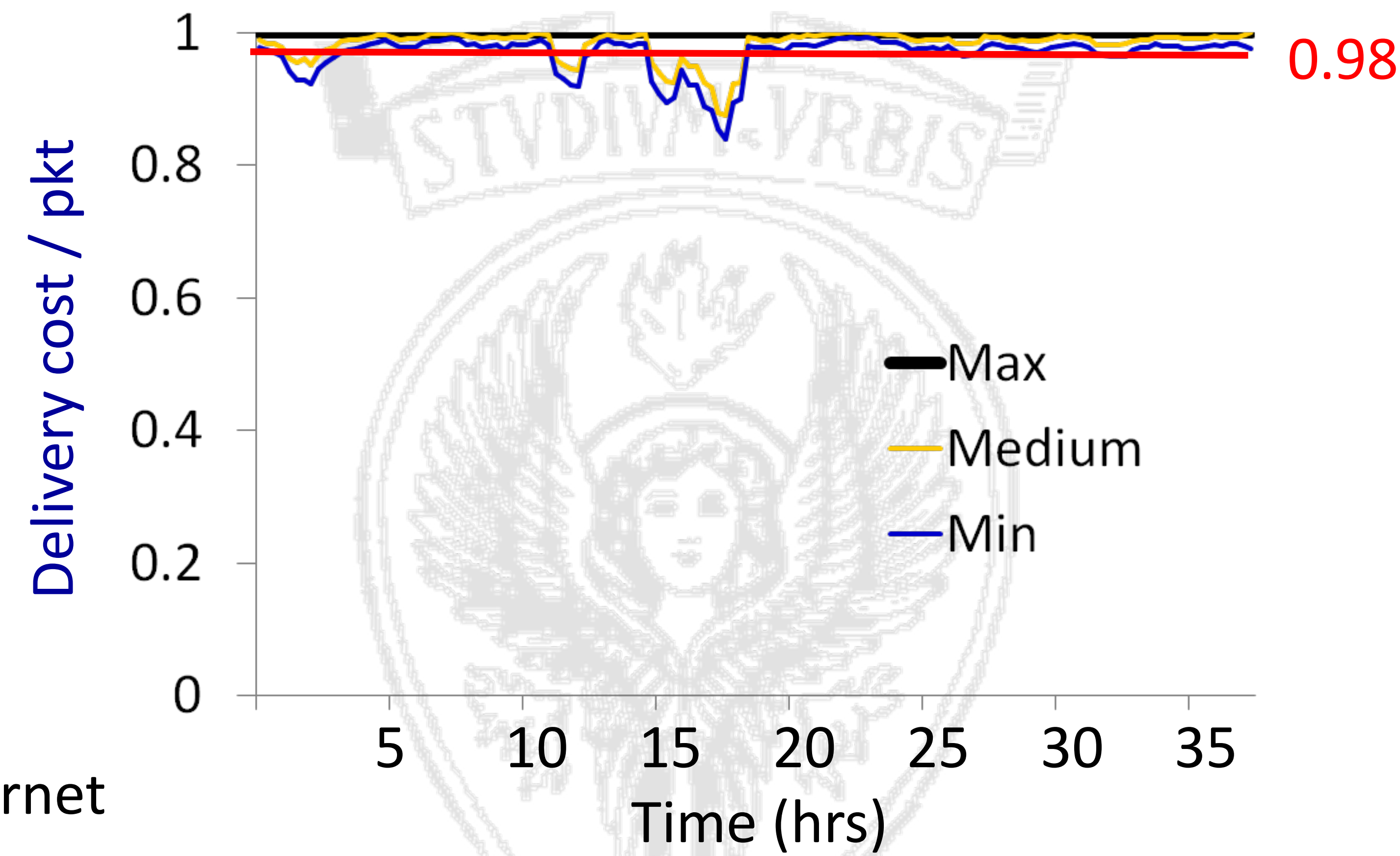


Twist



Mirage

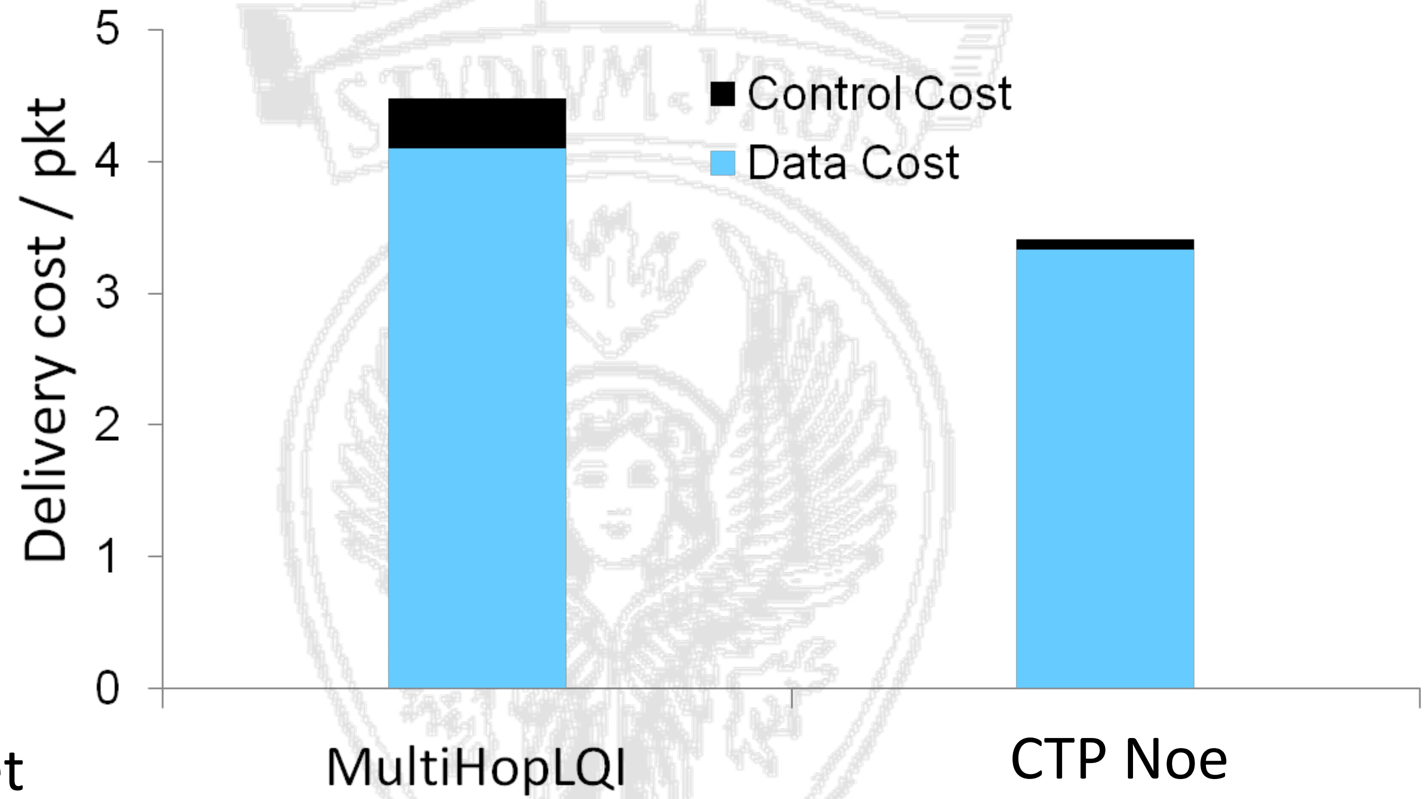




Tutornet

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

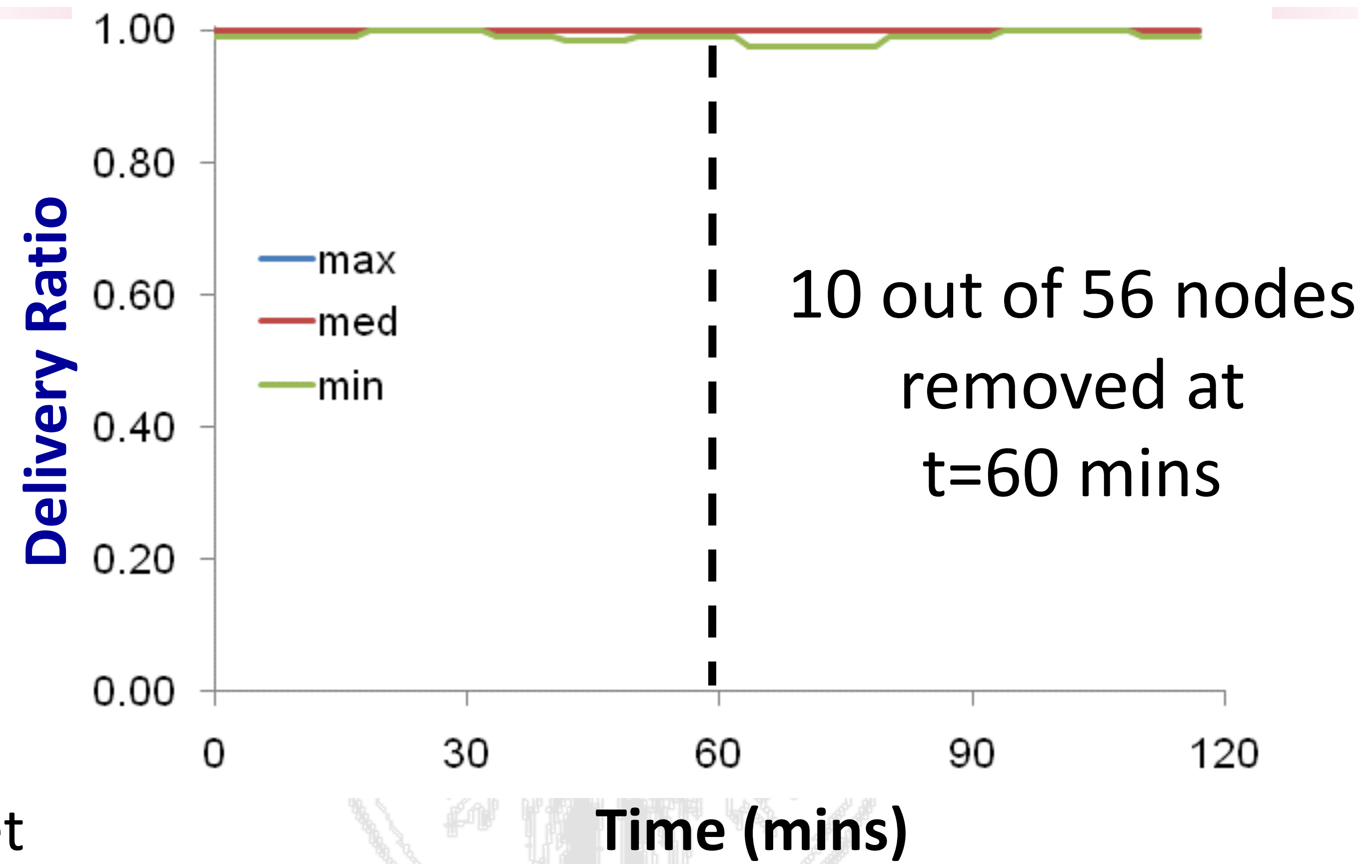
Tutornet



Low data and control cost

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

Low duty-cycle with low-power MACs

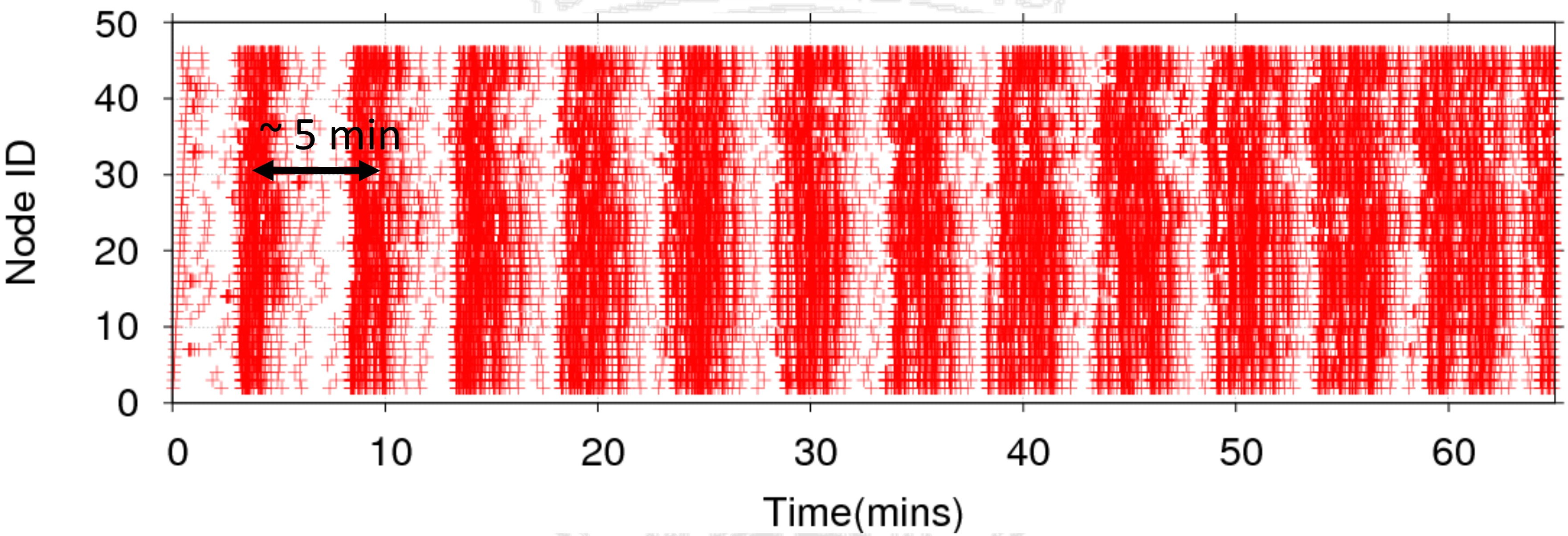


Tutornet

No disruption in packet delivery

Nodes reboot every 5 mins

Routing Beacons



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

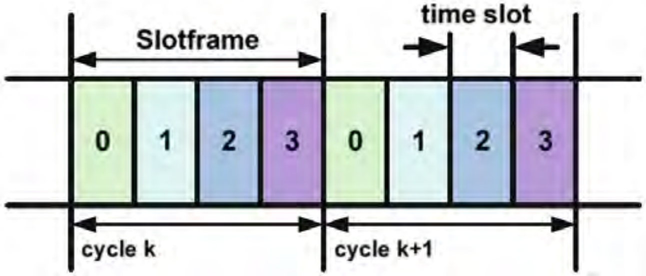
- Radio Frequency Identification Blink (BLINK) mode supports effective ID exchange for sake of item/people identification, location, and tracking
- Asynchronous multi-channel adaptation (AMCA) supports dynamic multi-channel use in distributed beaconless networks
- Deterministic and Synchronous Multi-channel 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

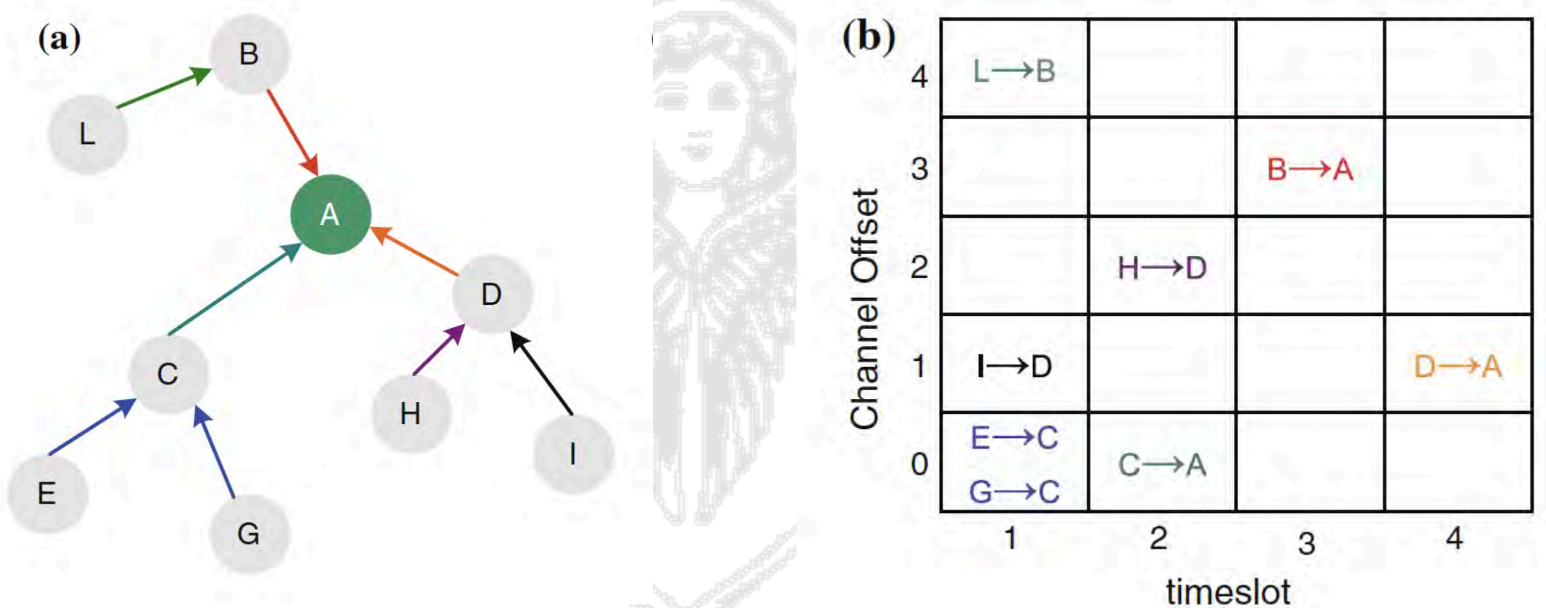
- Nodes synchronize on a periodic slotframe consisting of x timeslots (case x=4 in the figure).



- 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

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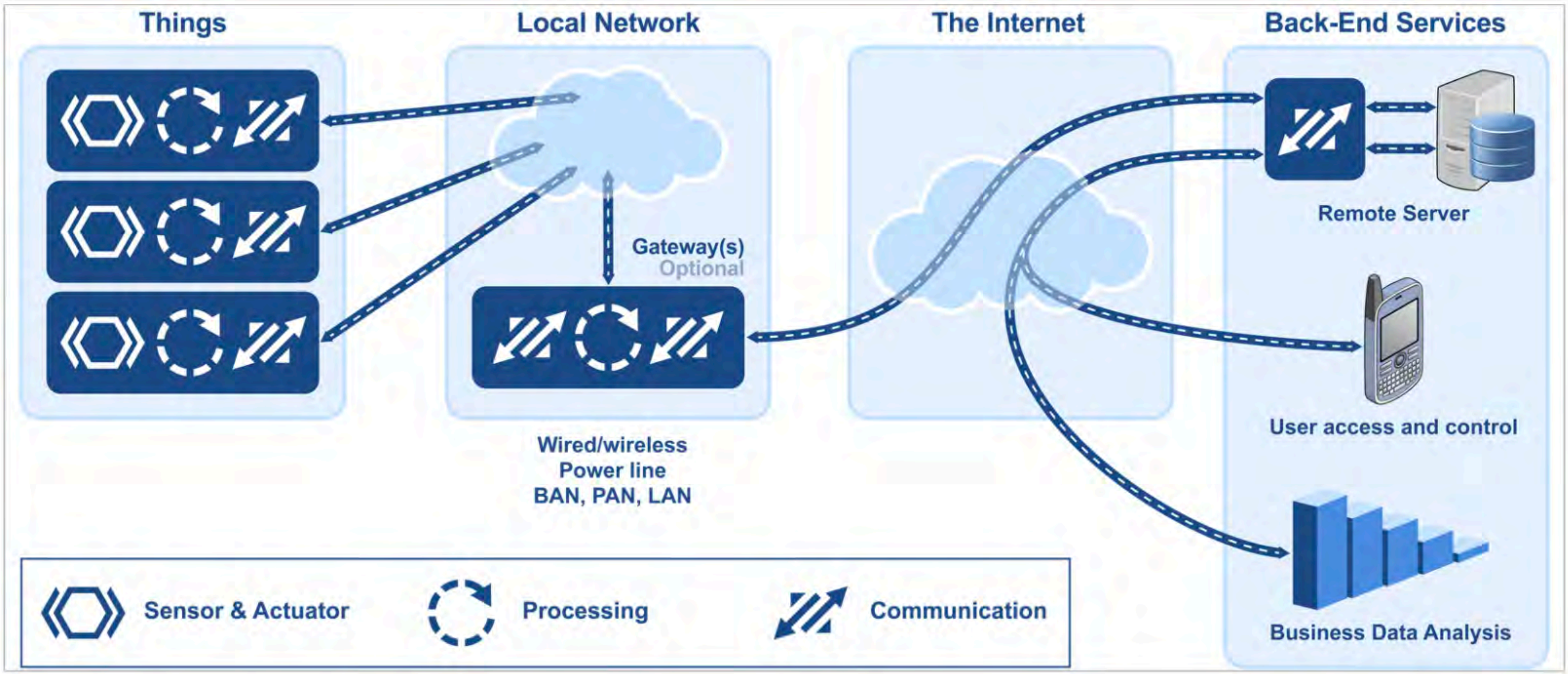
Current Scenario



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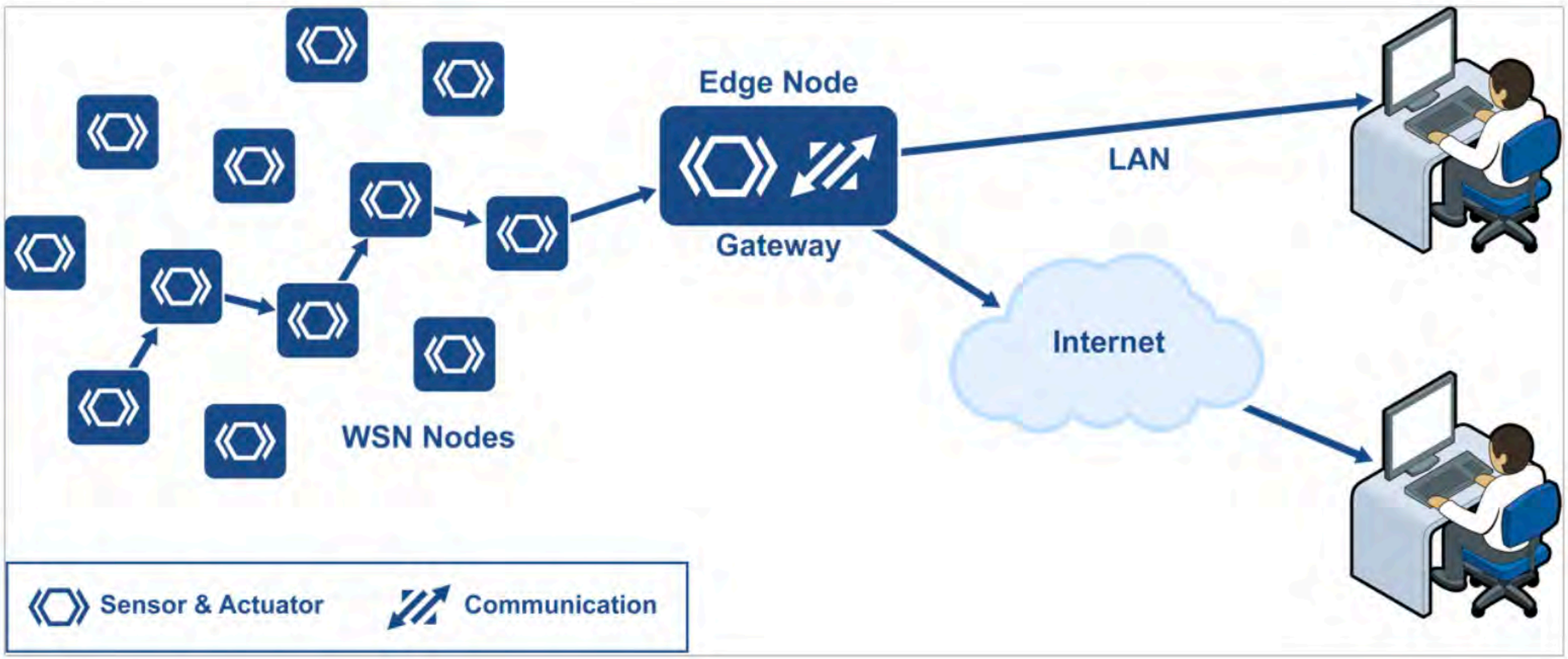

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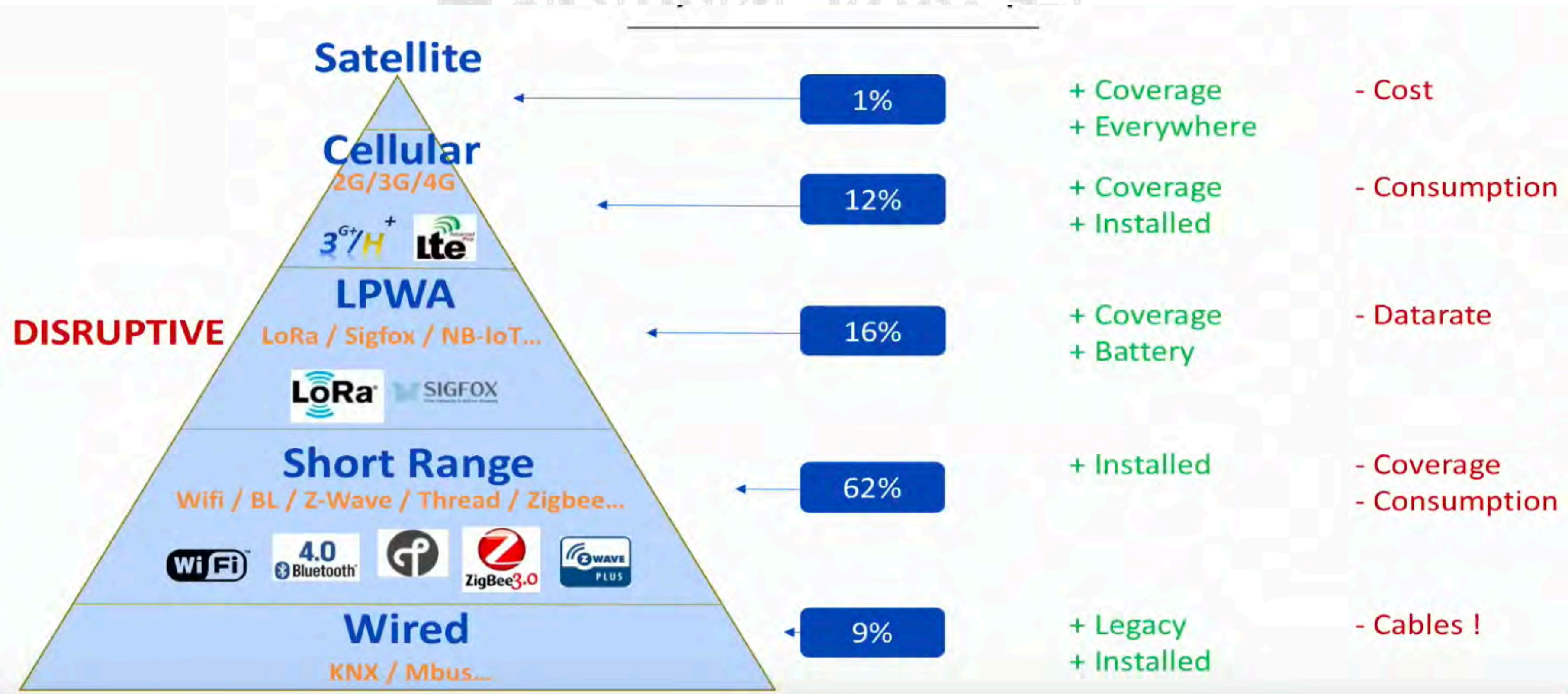

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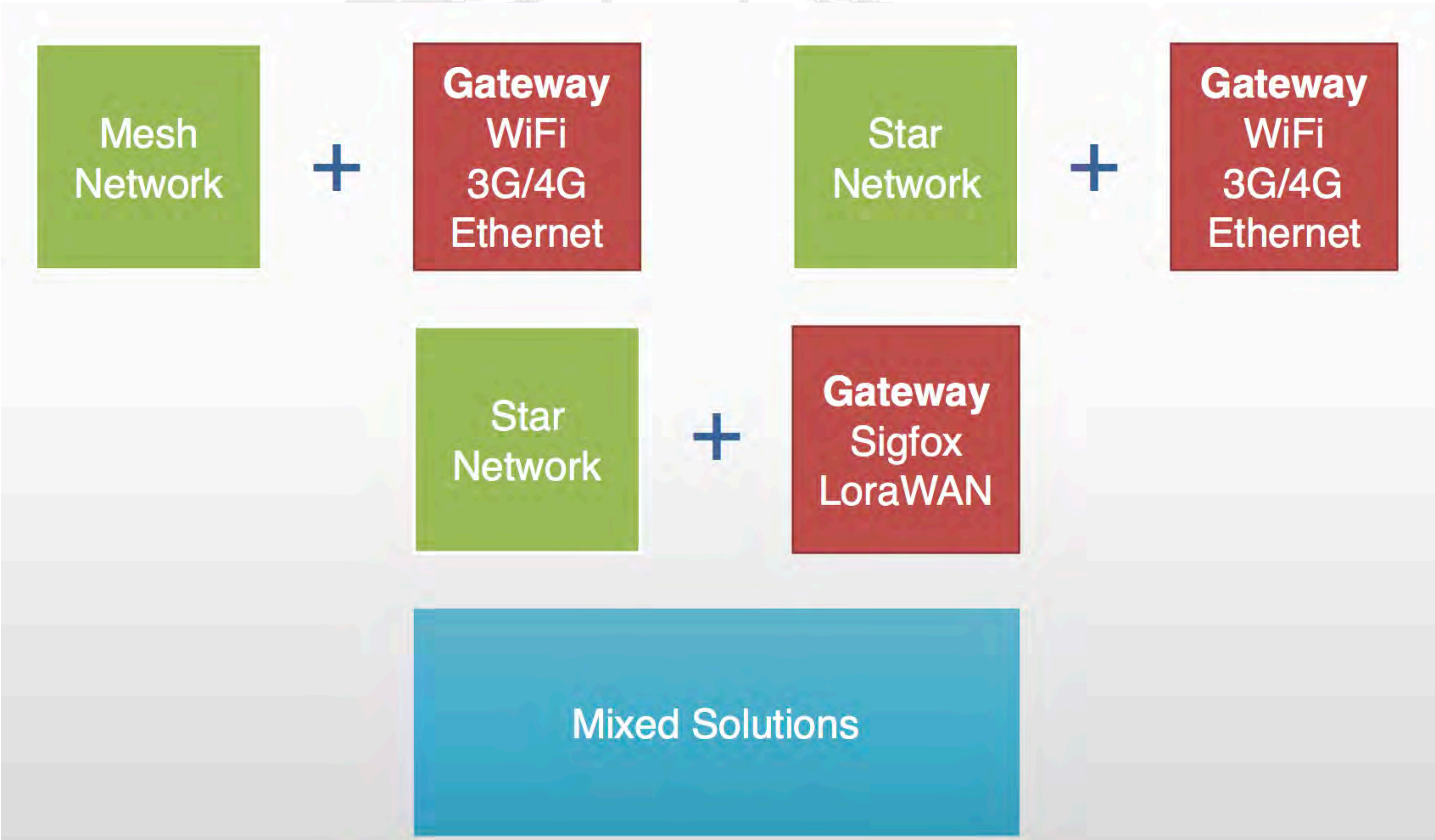


Requirements

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

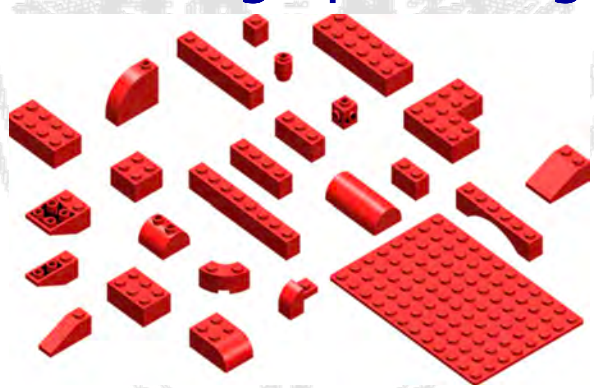
System Optimization

Useful methodologies

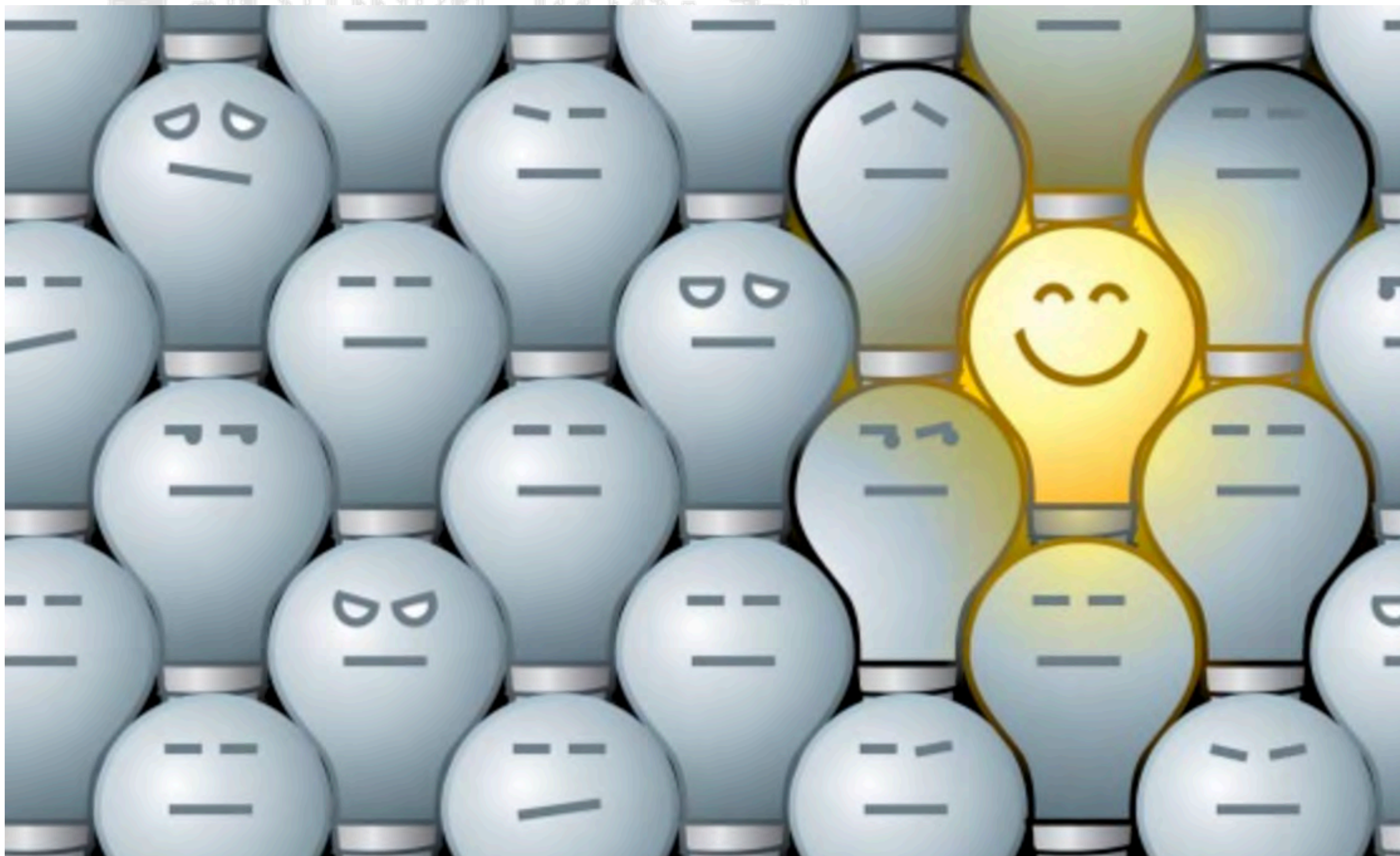
Idea → [Proof/analysis]→Solution Simulation→Field Test

System Optimization

What we are doing…providing you with the



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



IoT Innovation

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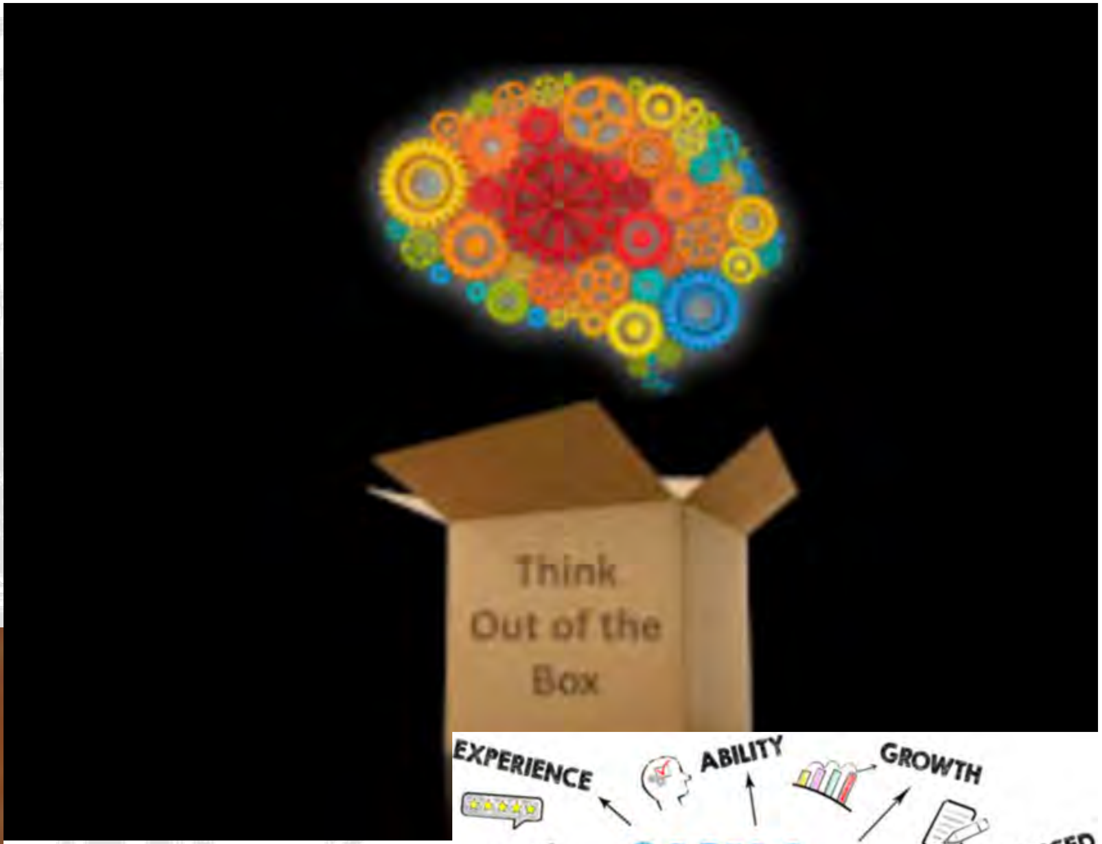
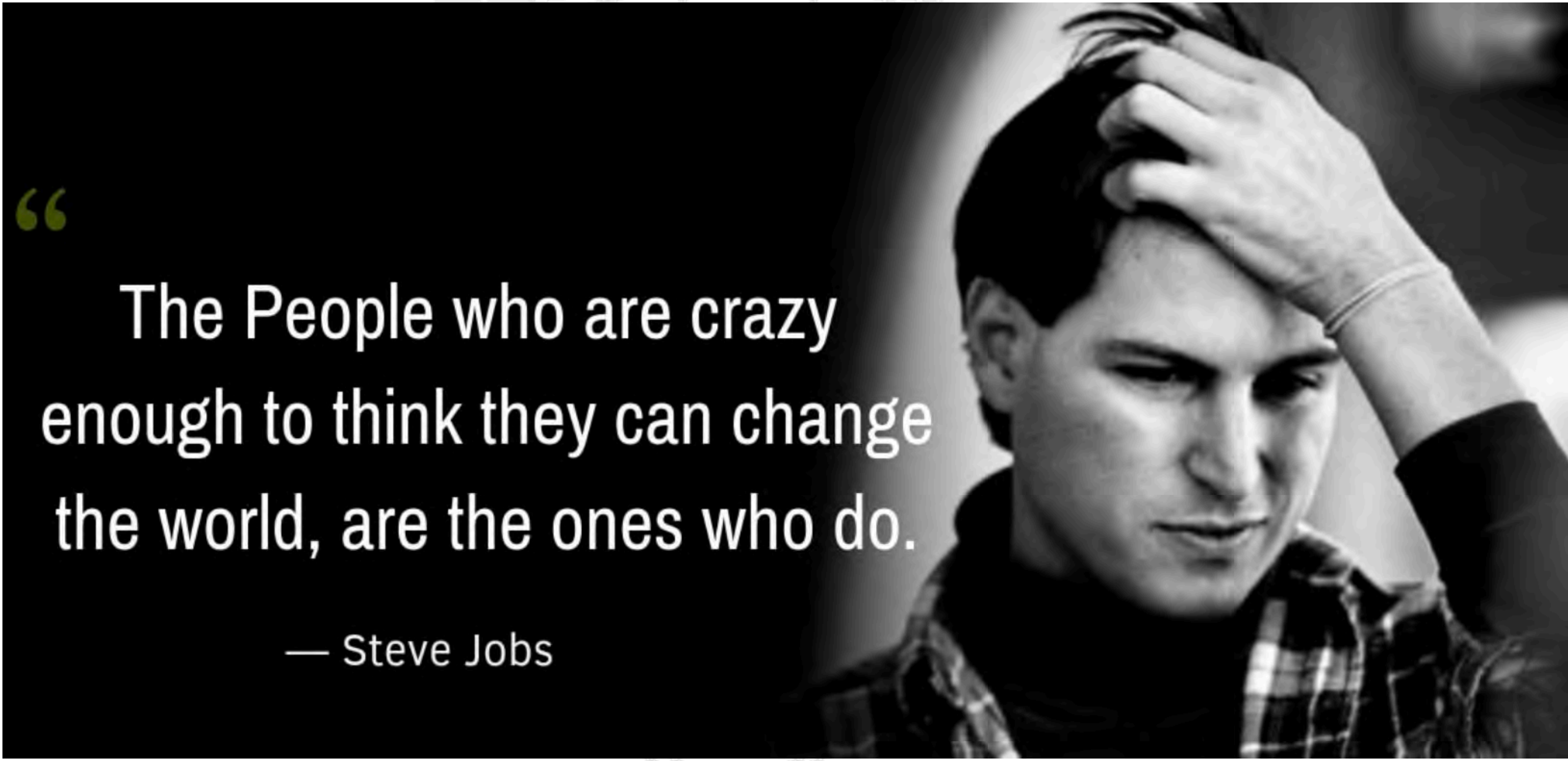
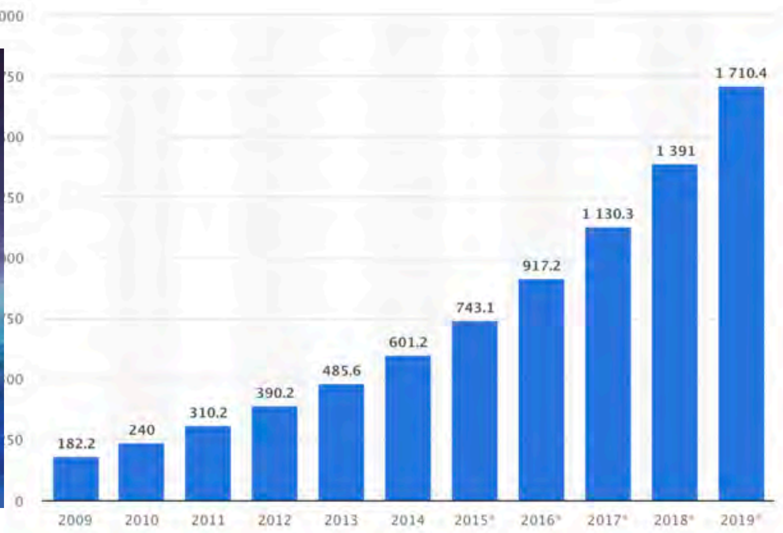
Innovation Training




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 ?



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2012
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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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- Today 500Bln

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- 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.

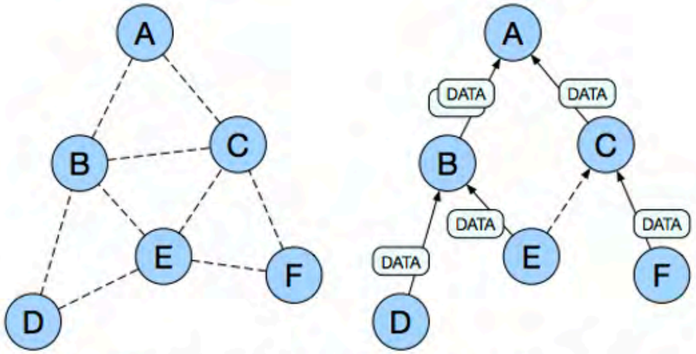
RPL, 2012

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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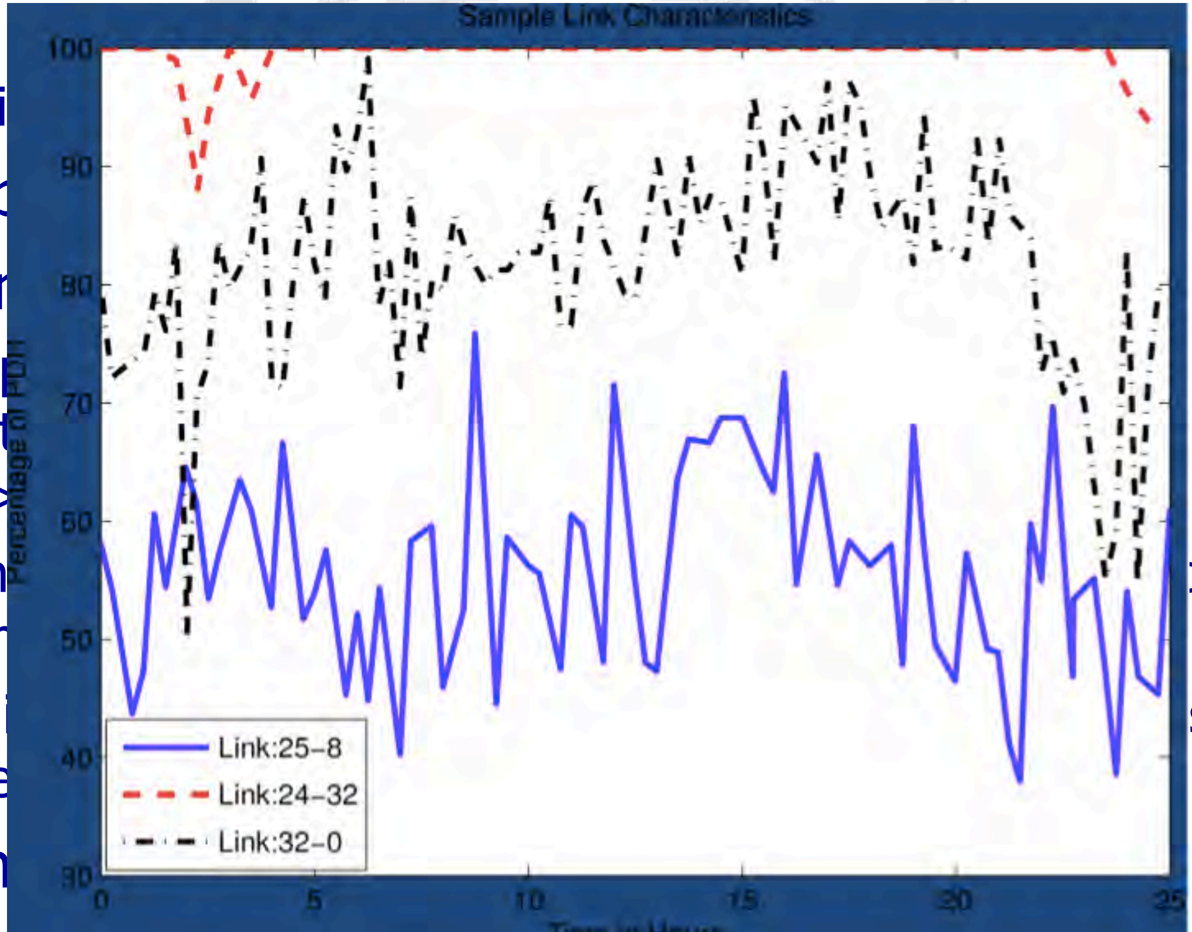
ROLL--Routing Over Low power and Lossy

- “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 sar
  - dynami … s, all fast change



- Focus on
- Routing supported across multiple types of link layers

ROLL--Routing Over Low power and Lossy

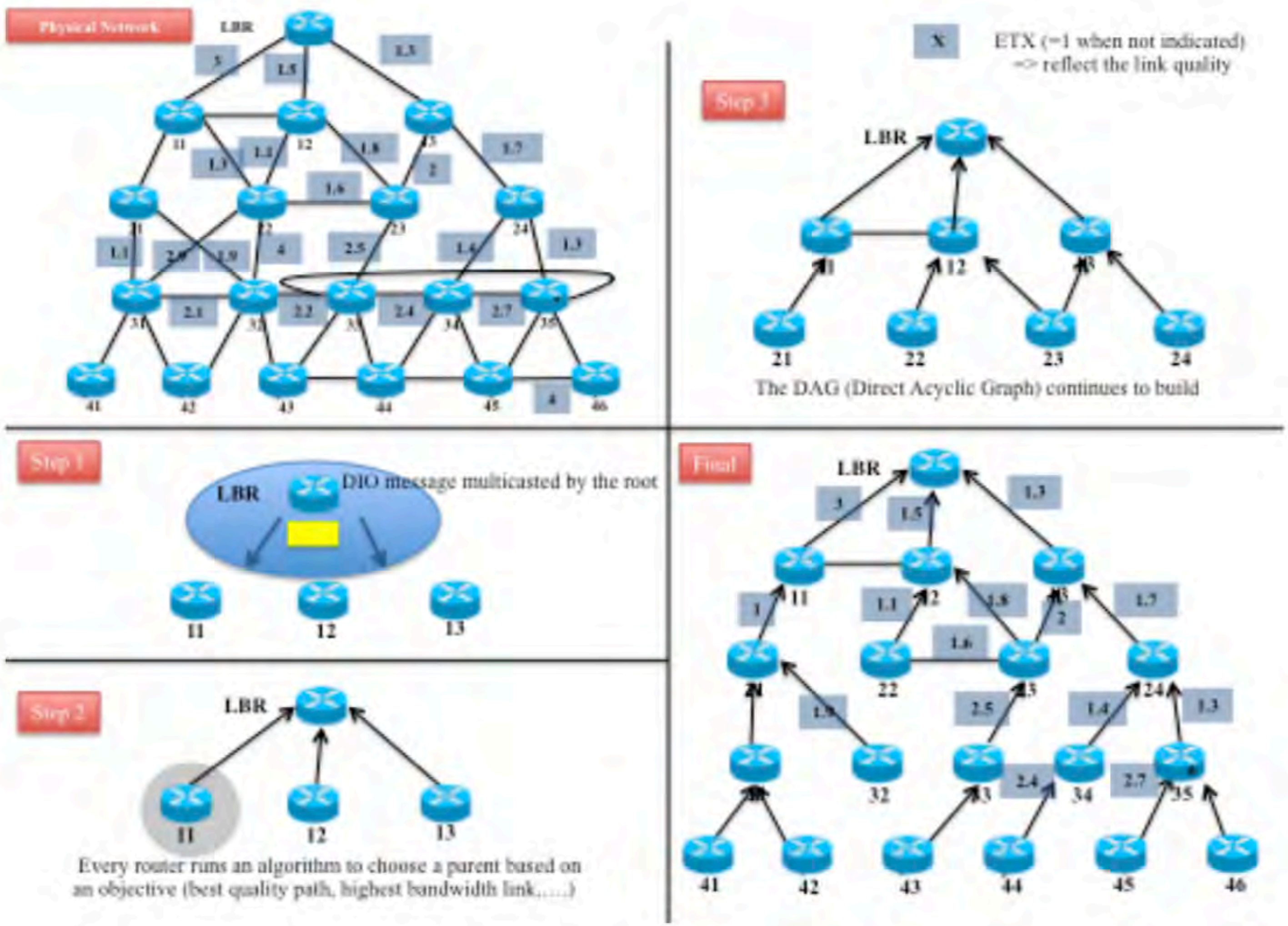
- “Ripple” routing protocol RPL-- Proactive distance vector routing;
  - specifies how to build a destination oriented acyclic graph (DODAG)
- Multi-hop support
- Flexible metric
  - <Find paths with the best ETX and avoid non encrypted links> or <Find the best path in terms of latency while avoiding 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-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



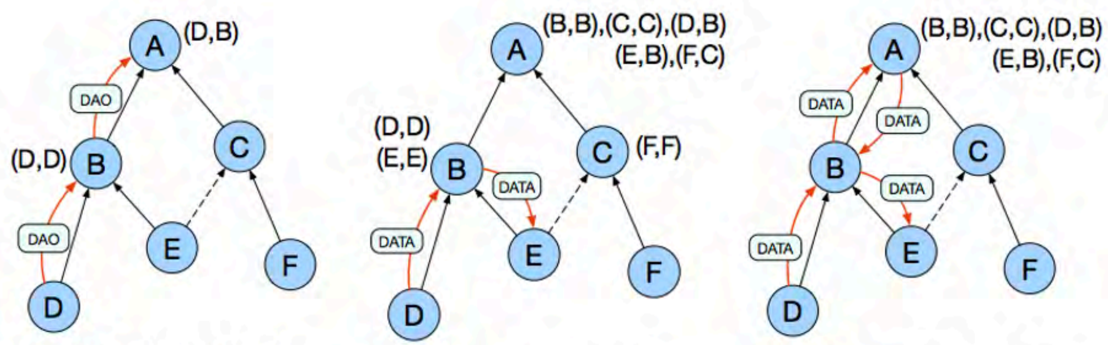
RPL -- How to multicast messages

- 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.

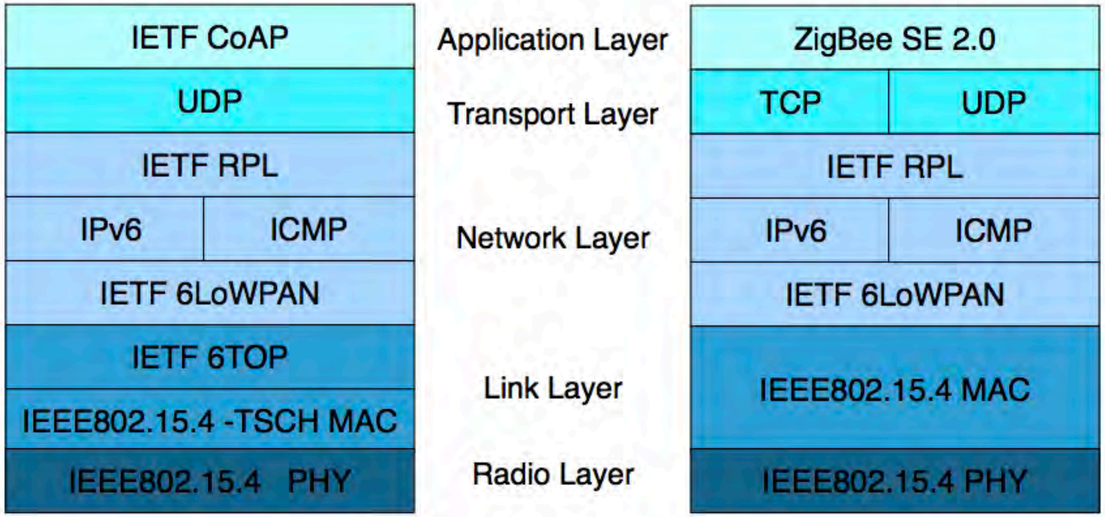
(d) Point-to-point communication: storing mode.

(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

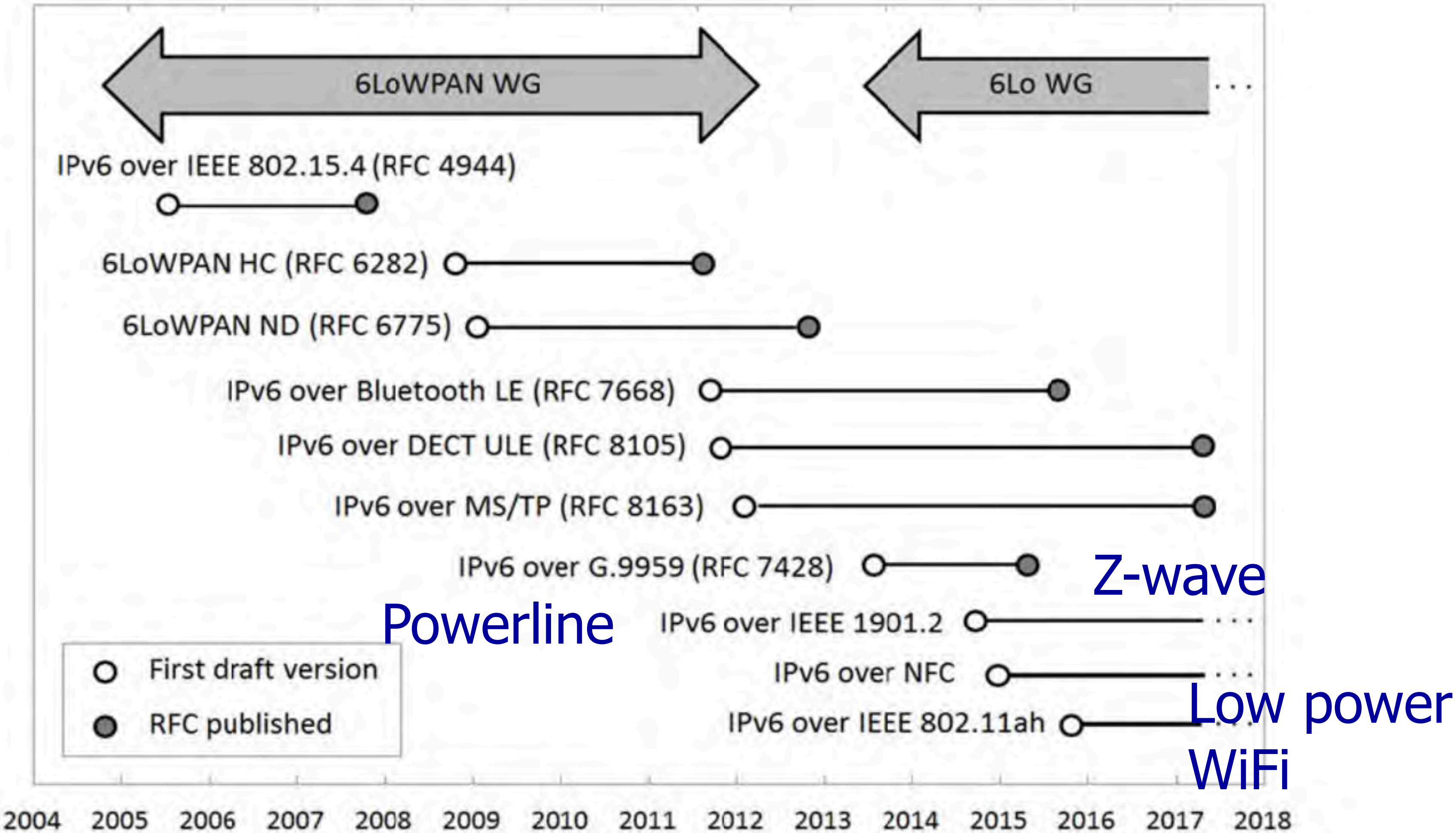


(a) IETF standardized stack. (b) ZigbeeIP stack.

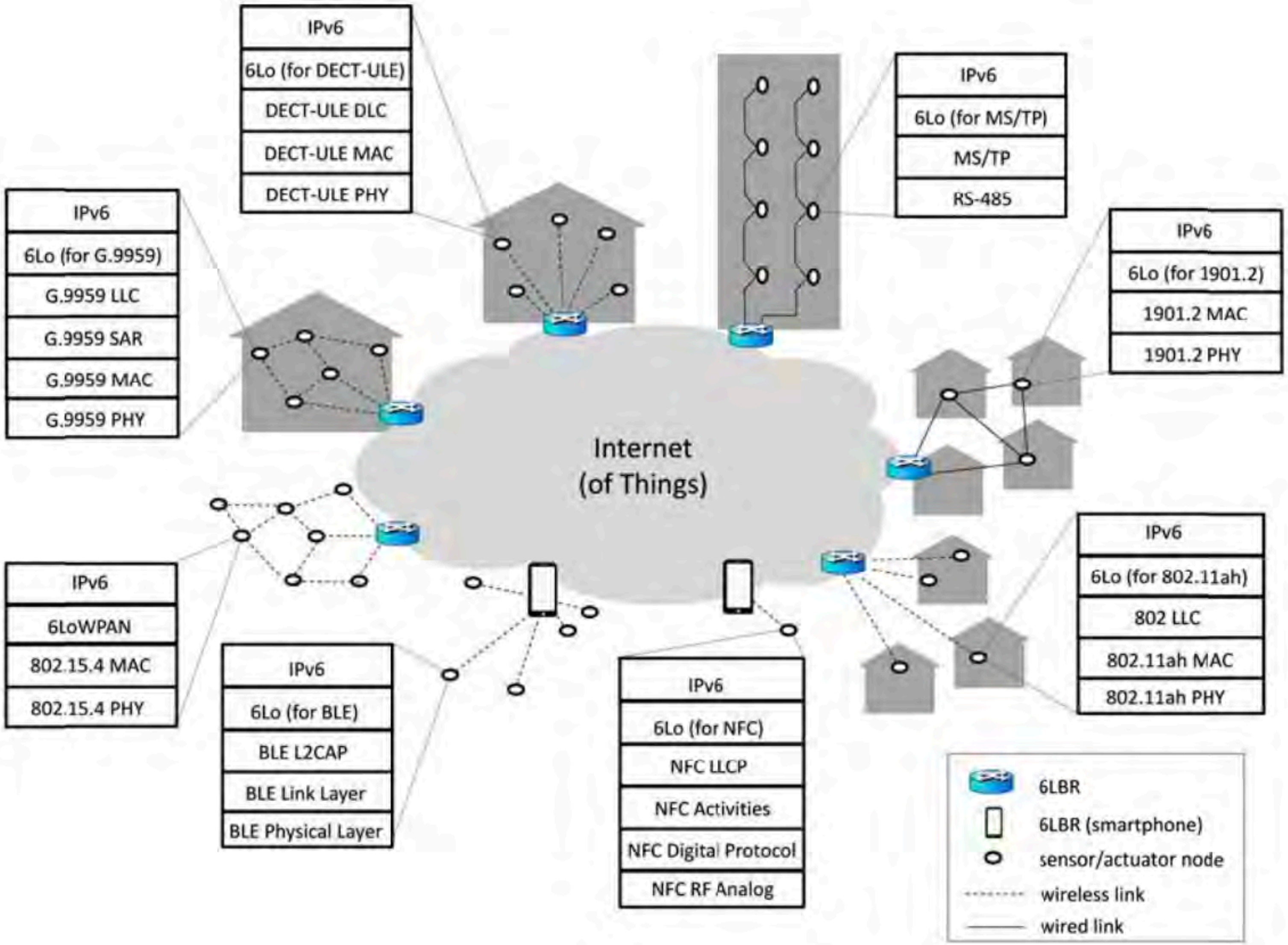
Further reading on 6Lo

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

Protocols for EH-WSNs

Internet of Things, a.a. 2020/2021

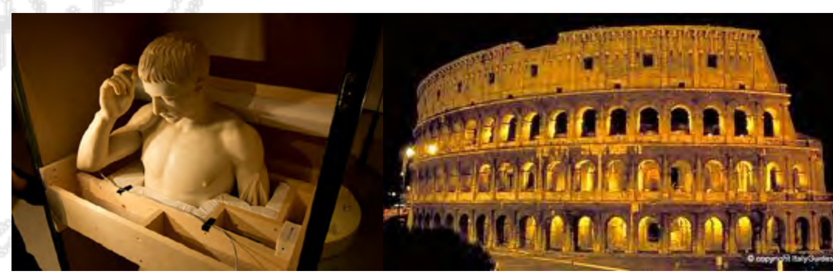
Un. of Rome "La Sapienza"

Chiara Petrioli[†]

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

Application scenarios

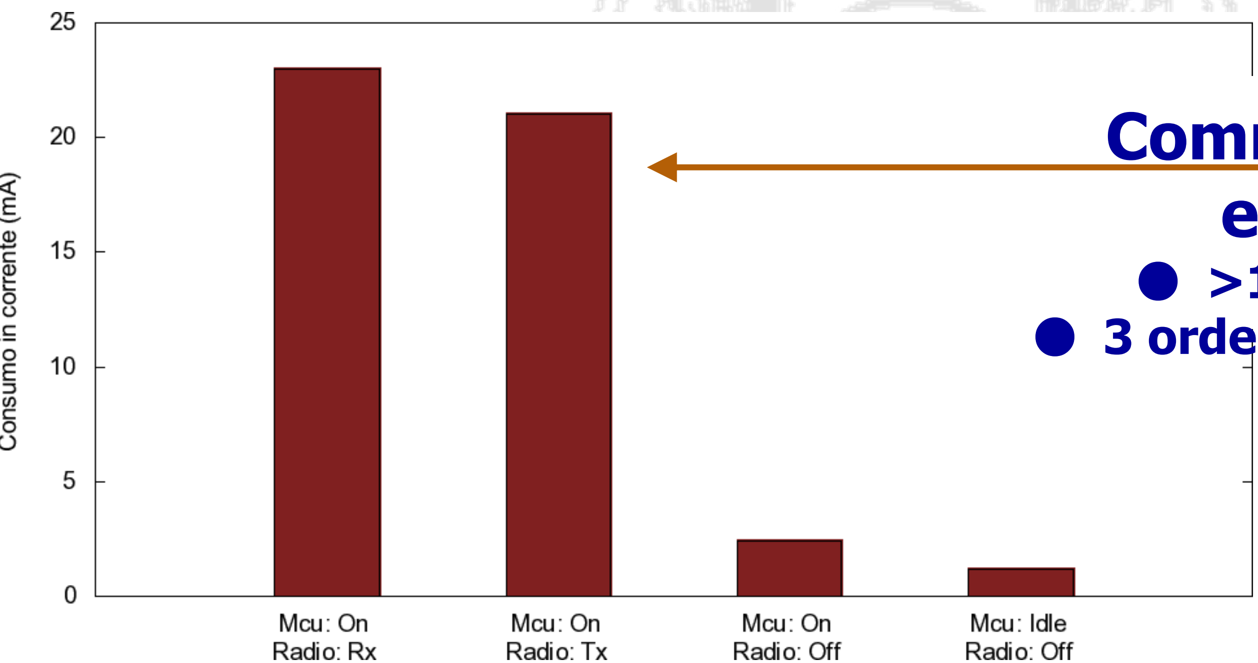
Structural health monitoring



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)

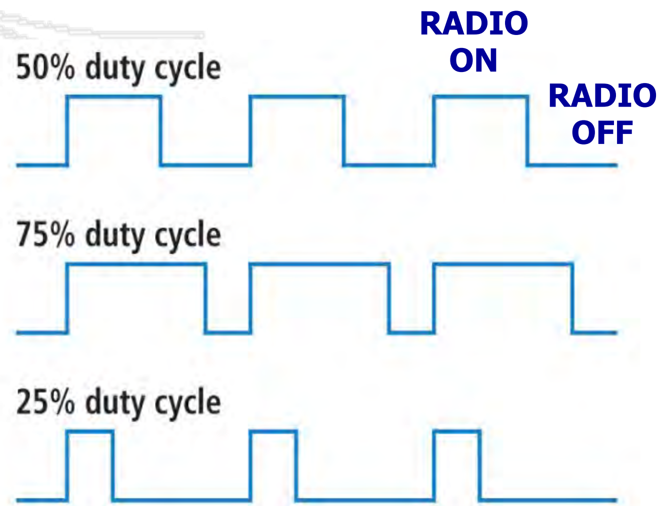


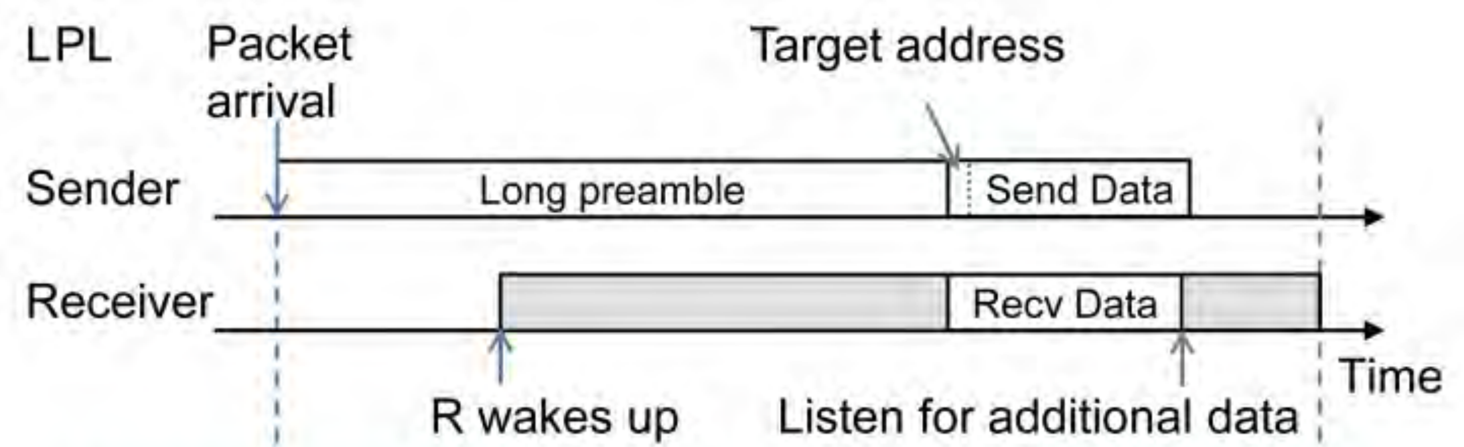
Communication is expensive!

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

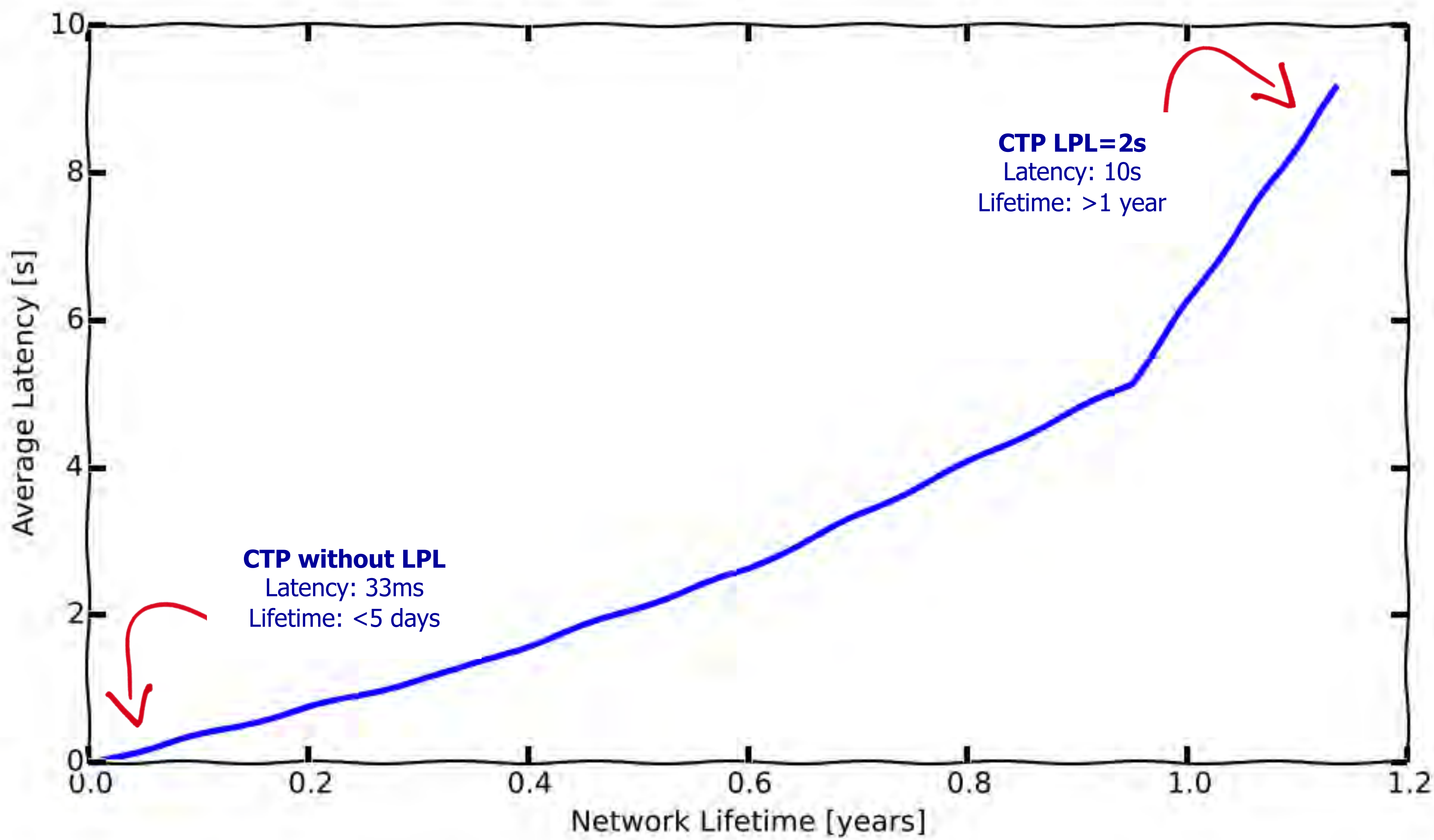
Standard Approach: Duty Cycling

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

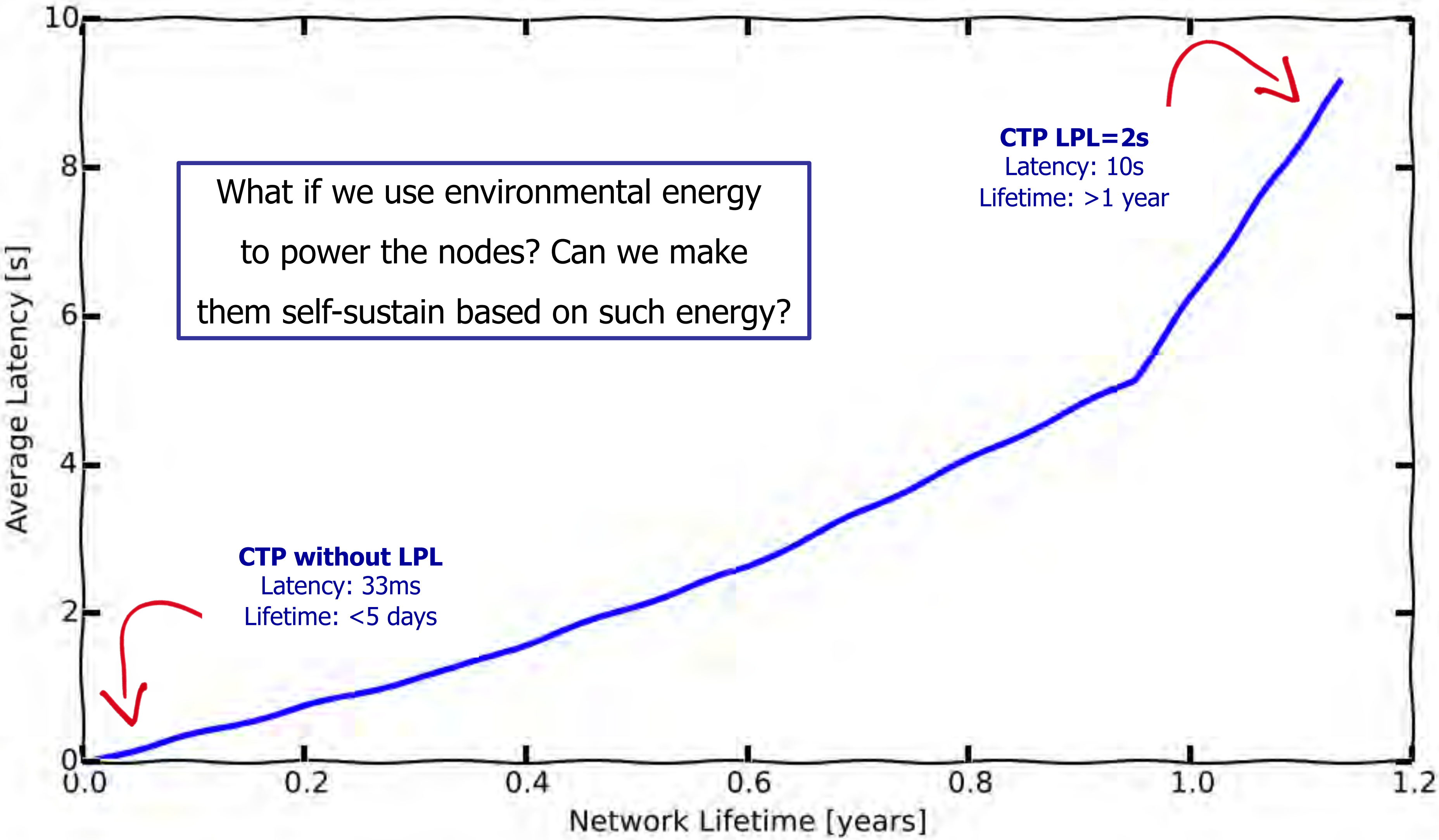




Latency vs. Energy Trade-off

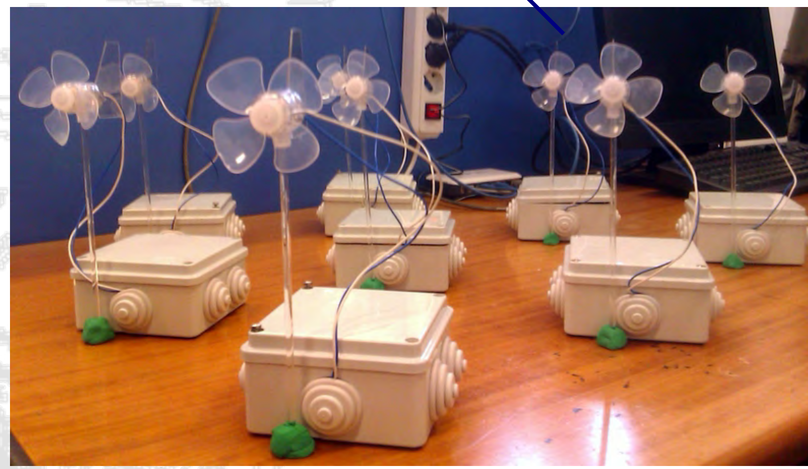


Latency vs. Energy Trade-off



What if we use environmental energy to power the nodes? Can we make them self-sustain based on such energy?

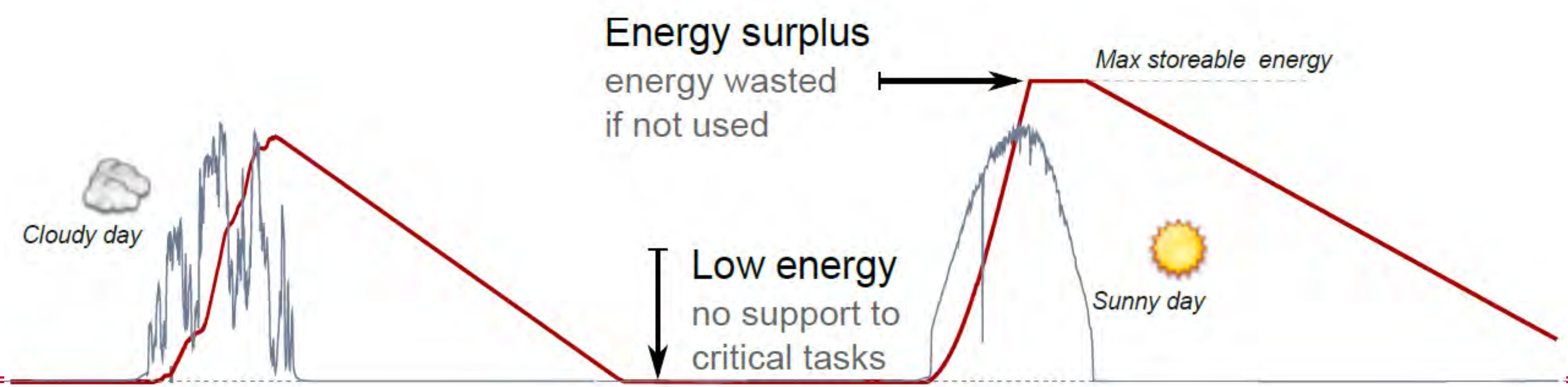
EH-WNS



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

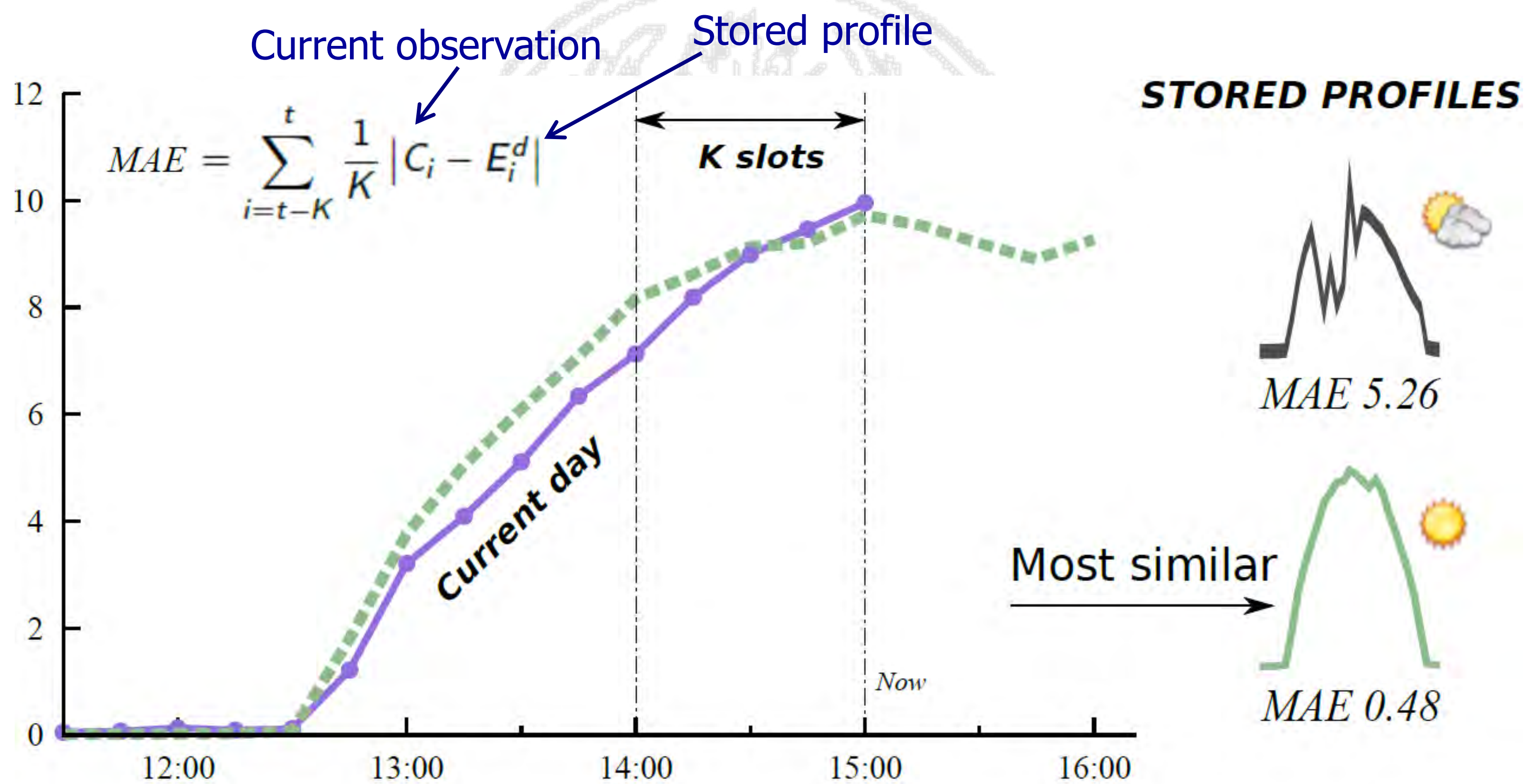
Why energy predictions?

- 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

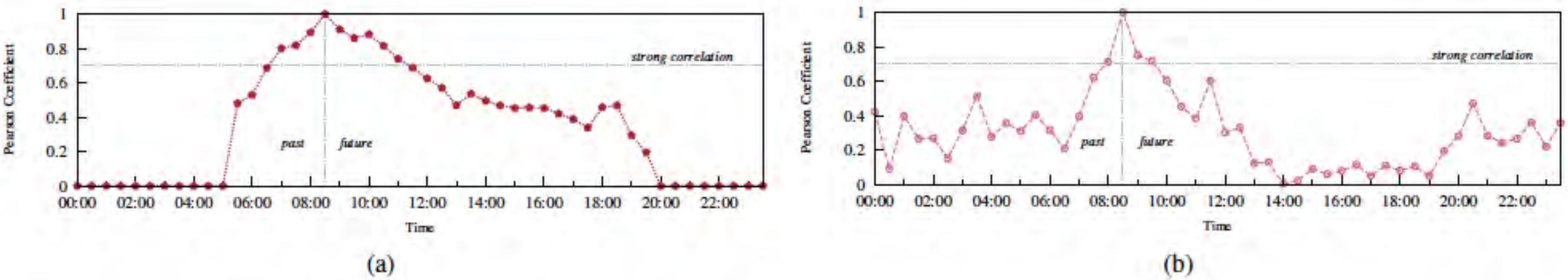


Figure 2. Pearson autocorrelation coefficient for (a) solar ORNL Dataset and (b) wind Bologna Dataset.

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

where:

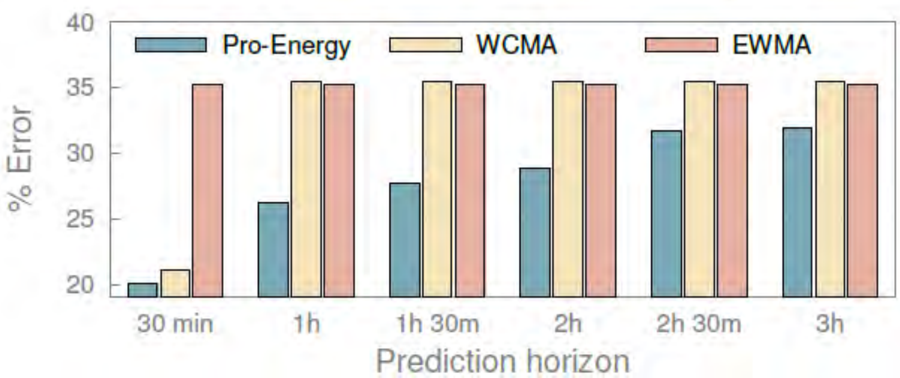
- α is the weighting factor defined in Equation (2);
- i is the i^{th} timeslot in the future, with respect to the current slot, t;
- G is the number of timeslots in the future which show a correlation above a given threshold with timeslot t;
- F is the number of future timeslots for which Pro-Energy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

Medium term energy prediction estimation

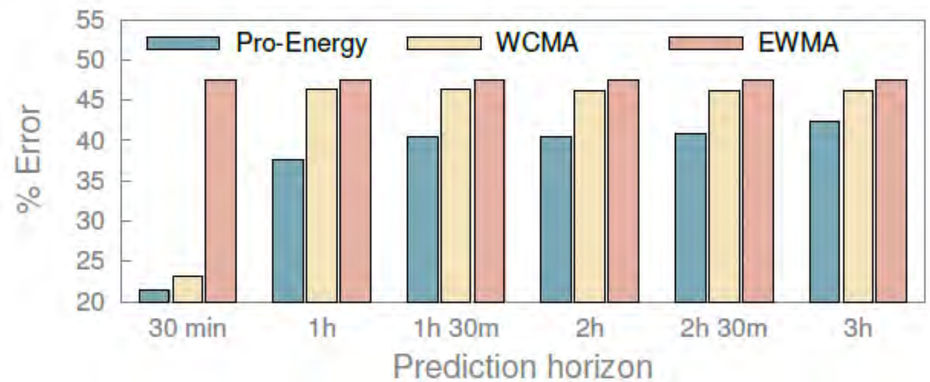
$$\hat{E}_{t+i} = \gamma_i \cdot C_t \; + \; (1 - \gamma_i) \cdot E^d_{t+i}$$

Pro-Energy accuracy

Solar



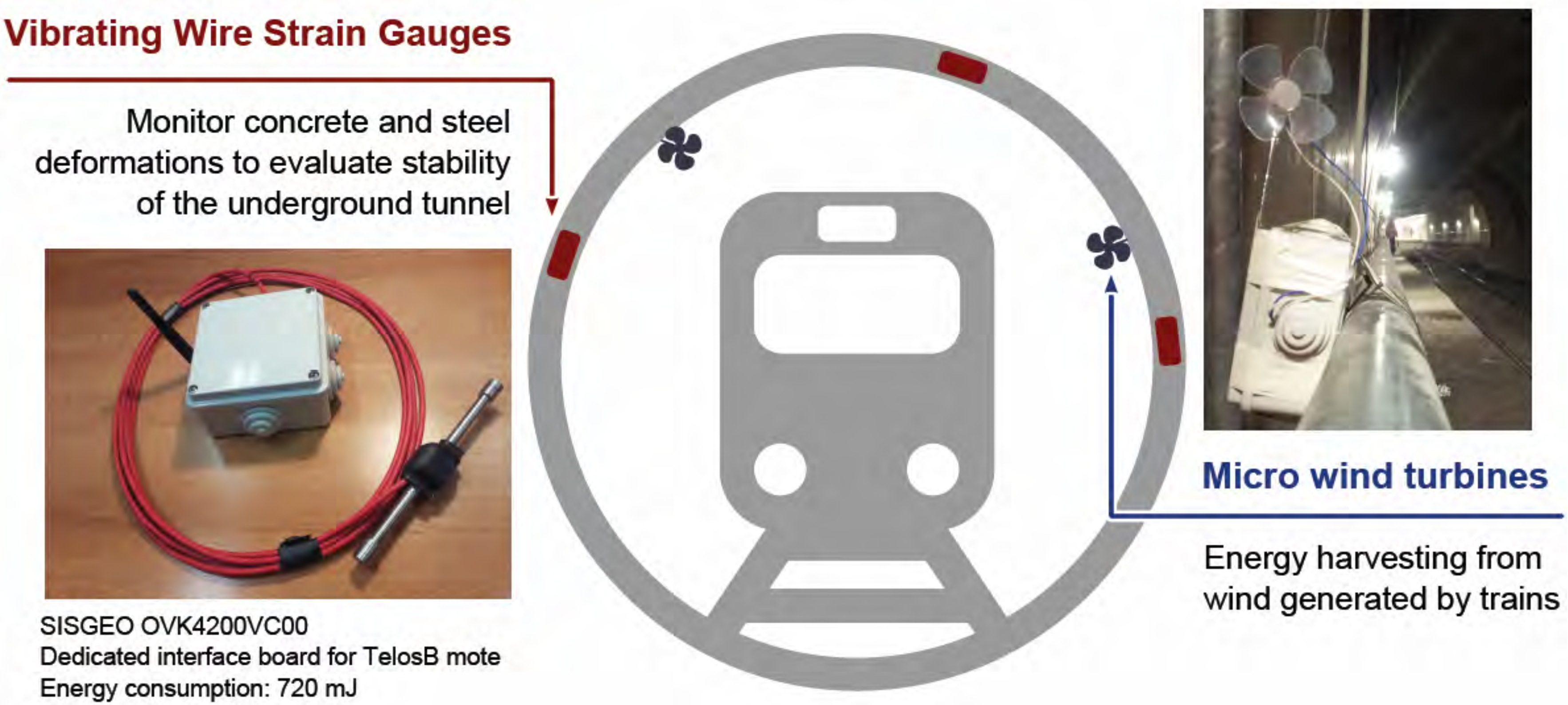
Wind



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



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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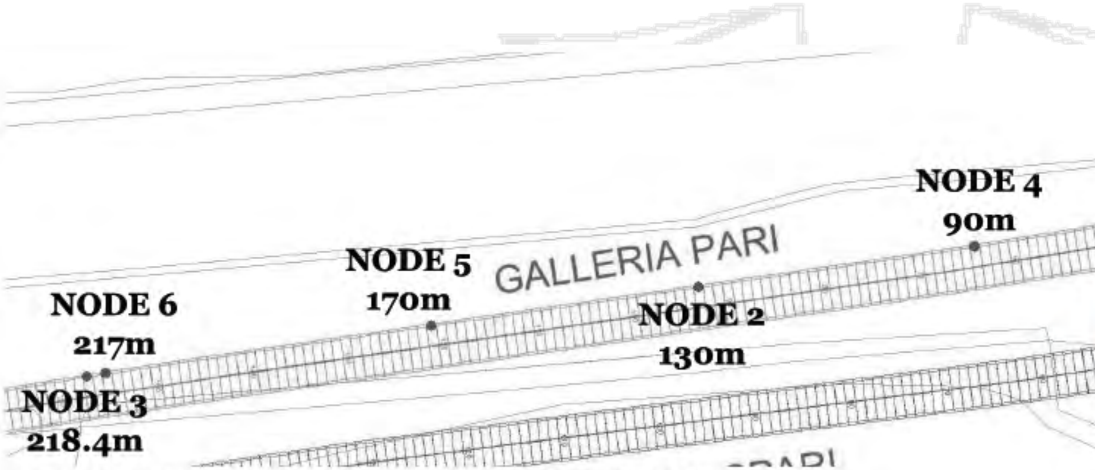
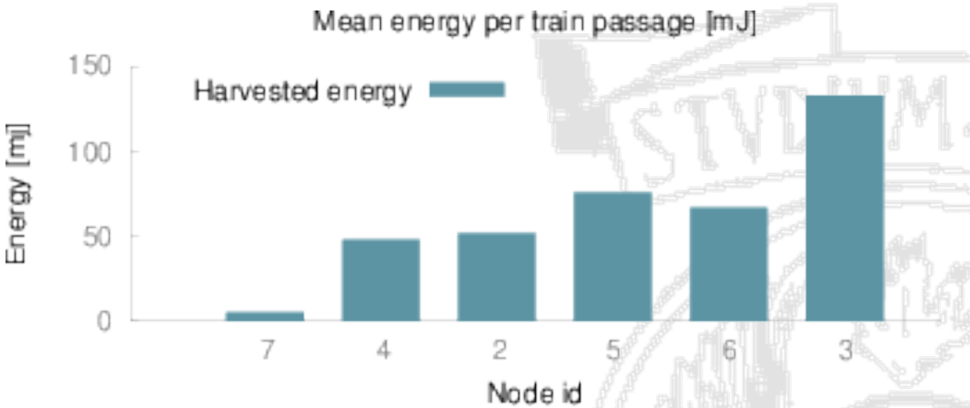
In-field air-flow data collection



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

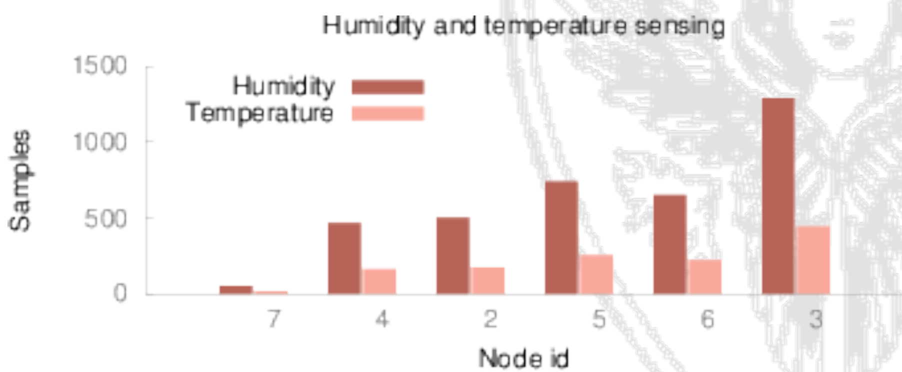
220 meter of instrumented tunnel
6 energy-harvesting nodes
33 days of data collection

Feasibility study

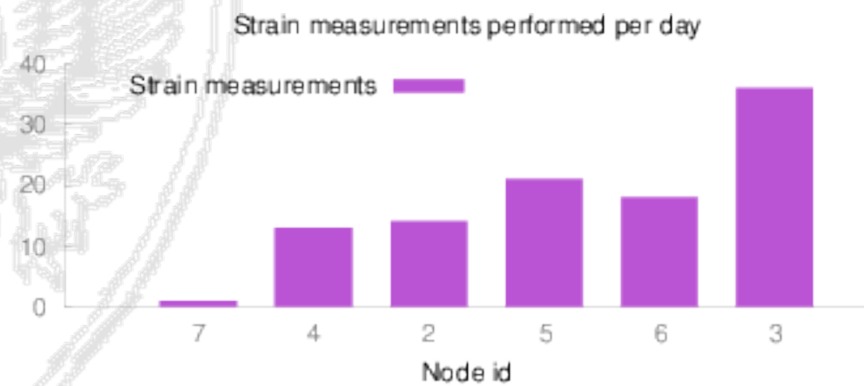


Up to 133 mJ harvested per train passage

Transmit/receive tens of KB



Collect hundreds of humidity and temperature samples

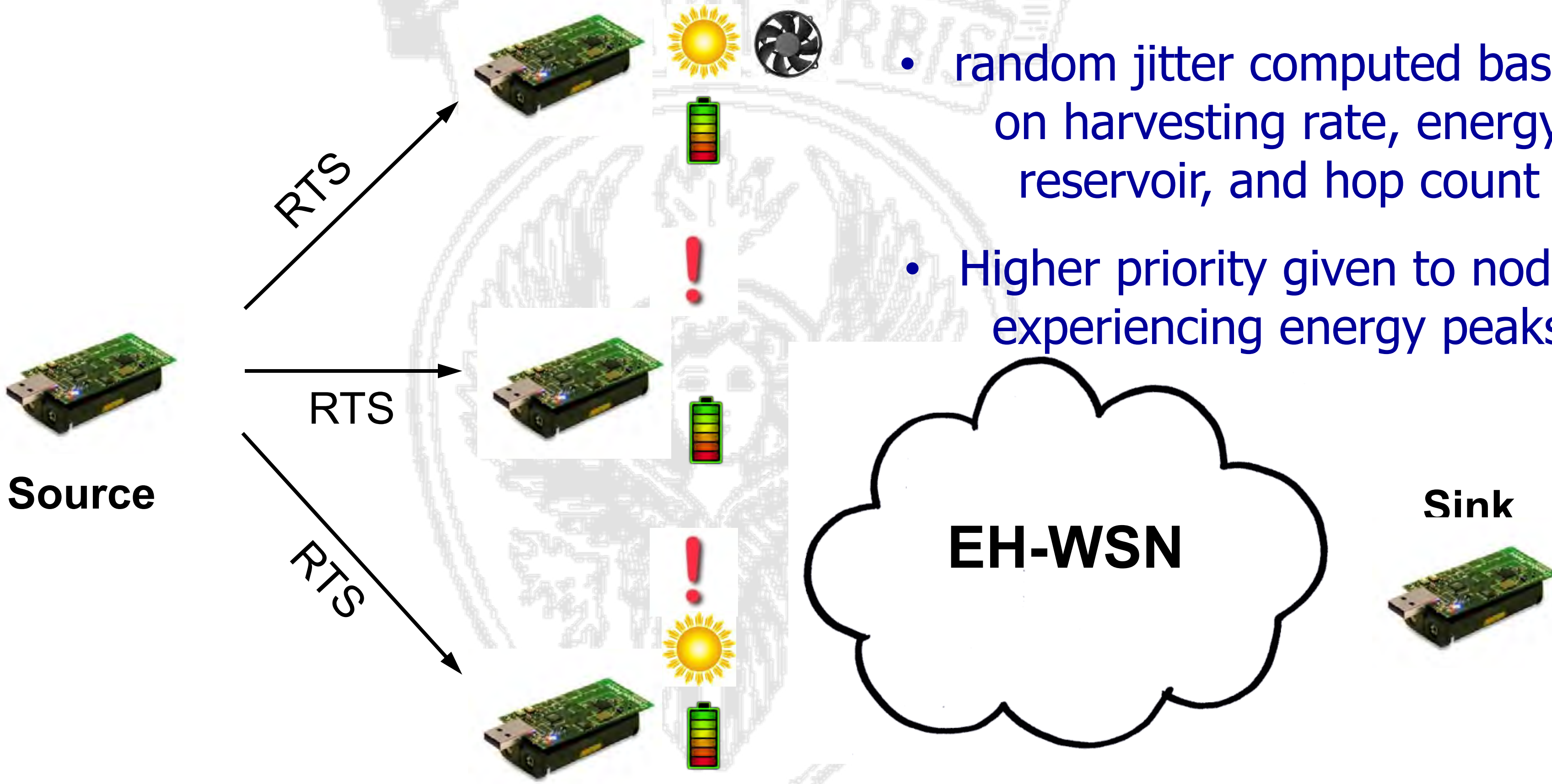


Up to 36 strain measurements per day

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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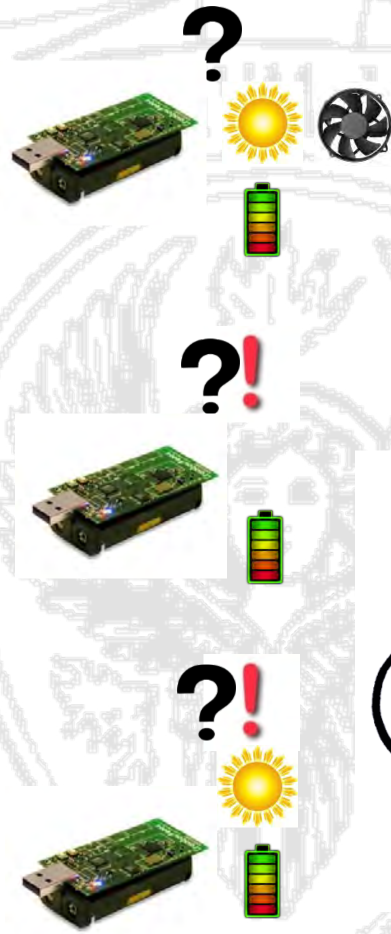
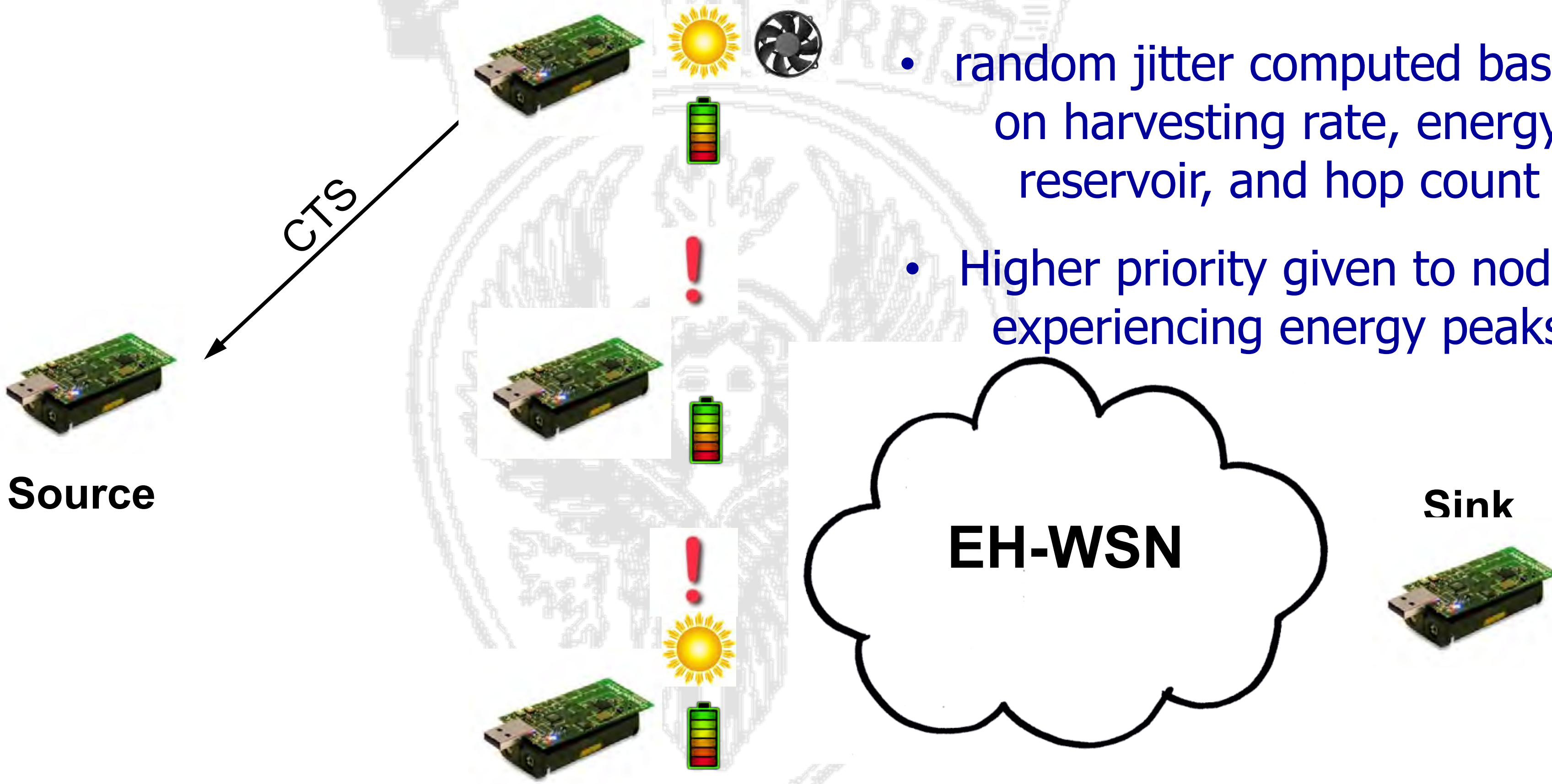


Harvesting-aware routing



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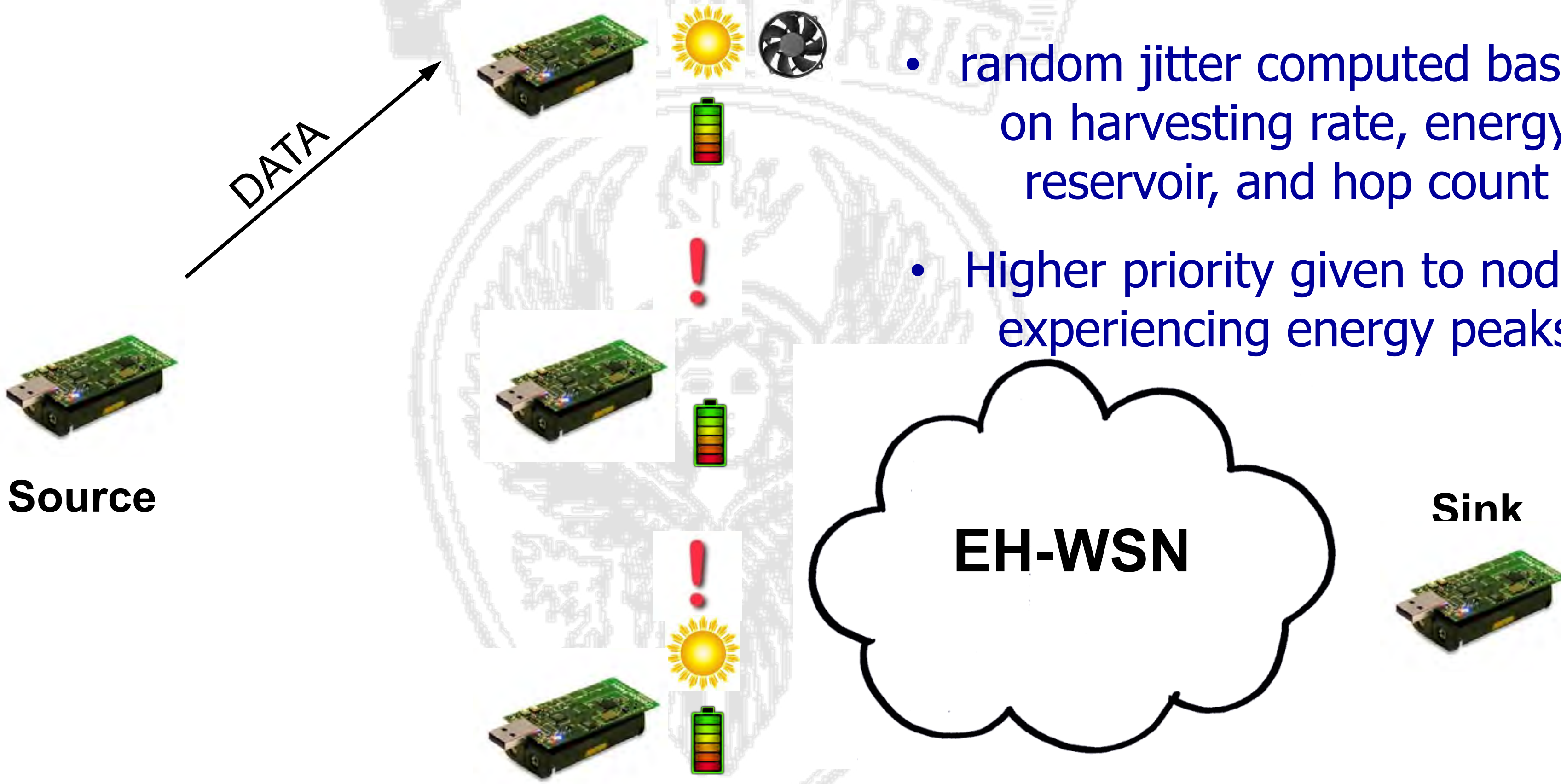
Harvesting-aware routing



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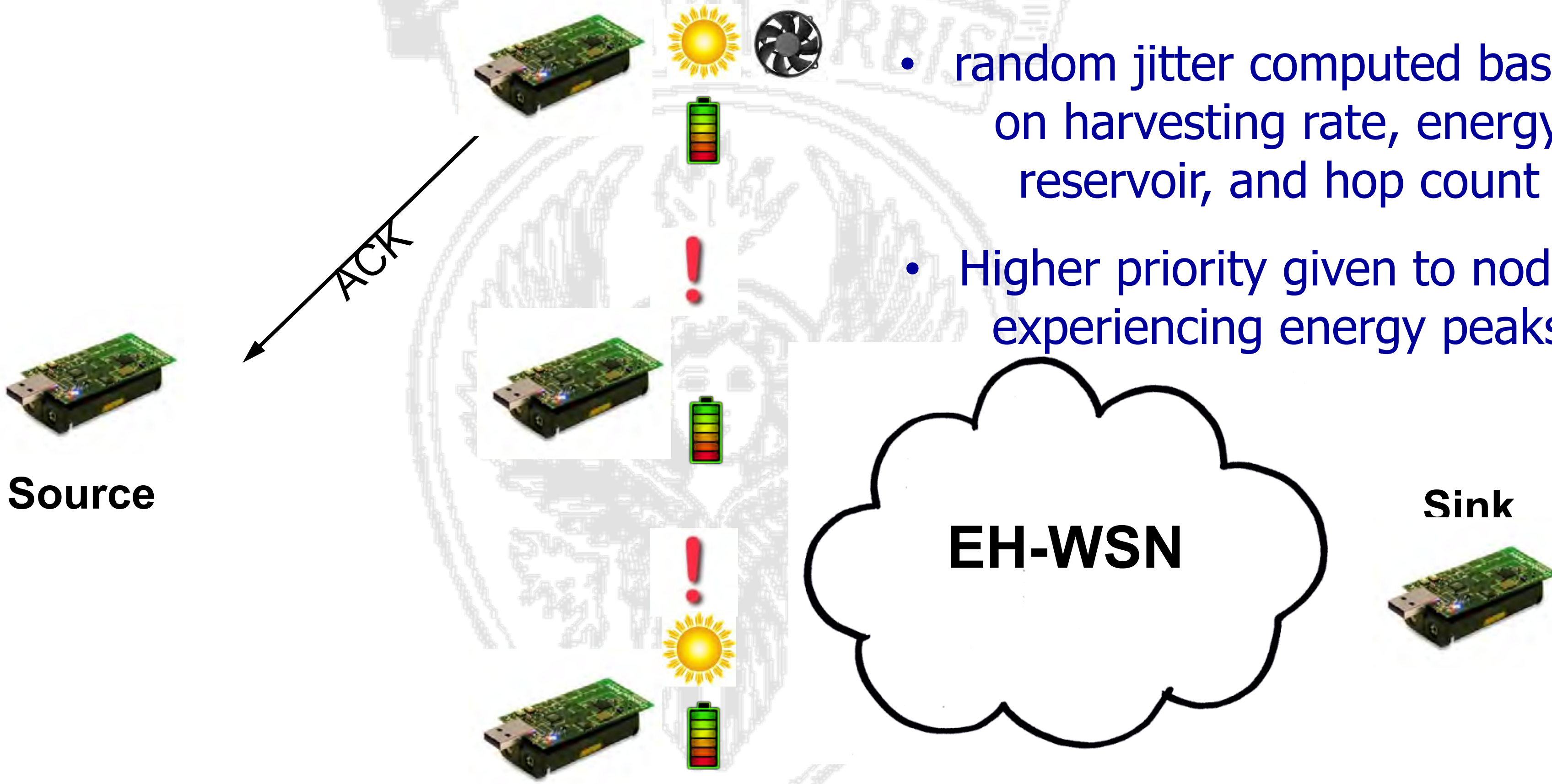

Timer-based contention:

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- Higher priority given to nodes experiencing energy peaks

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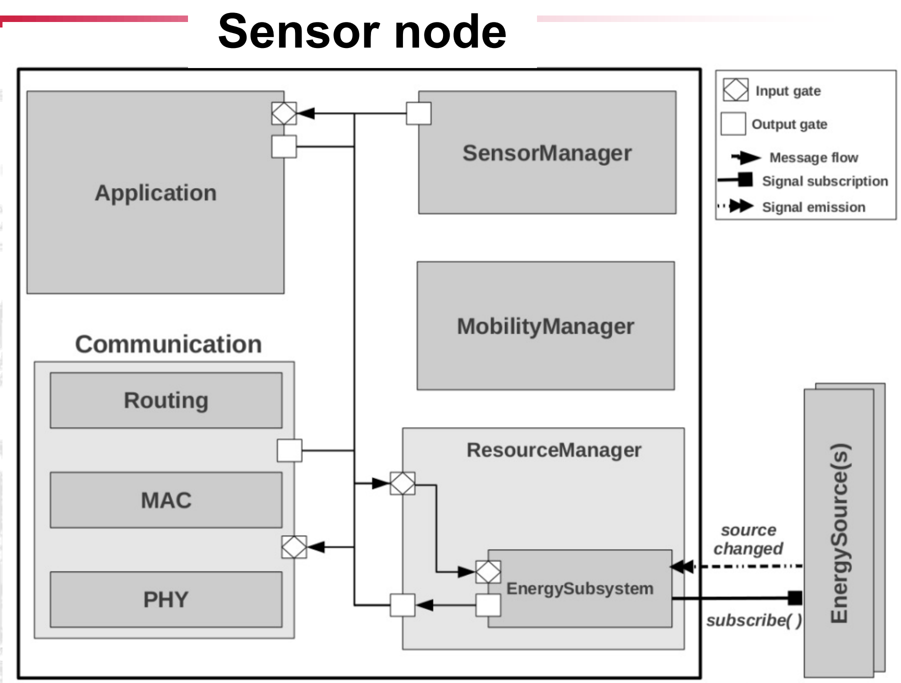
GreenCastalia: Motivation

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



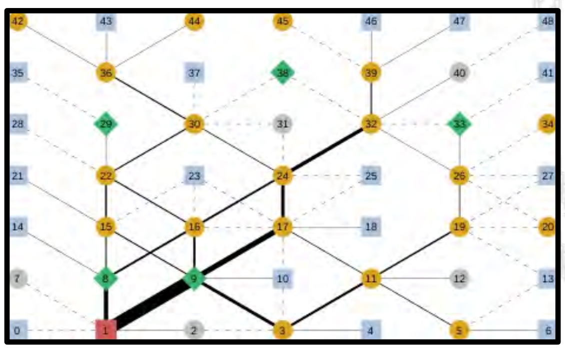
TraceEnergySource module: allows to feed the simulator with timestamped power traces collected through real-life deployments, or with energy availability traces obtained by data repositories or meteorological stations

Harvesting-aware routing: Results

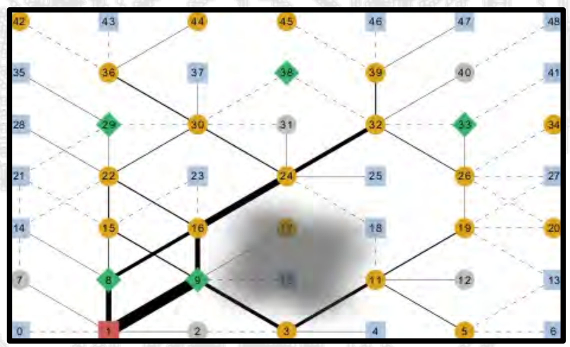
Simulation settings

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

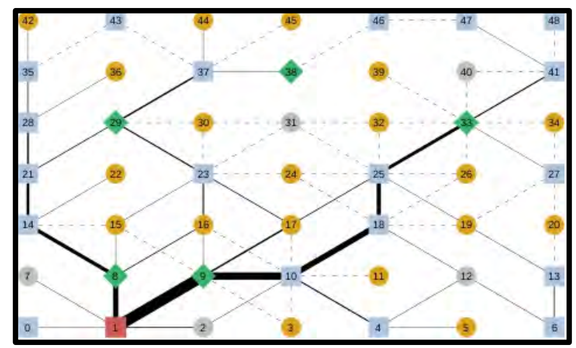
11am



5pm with shadow zone



8pm

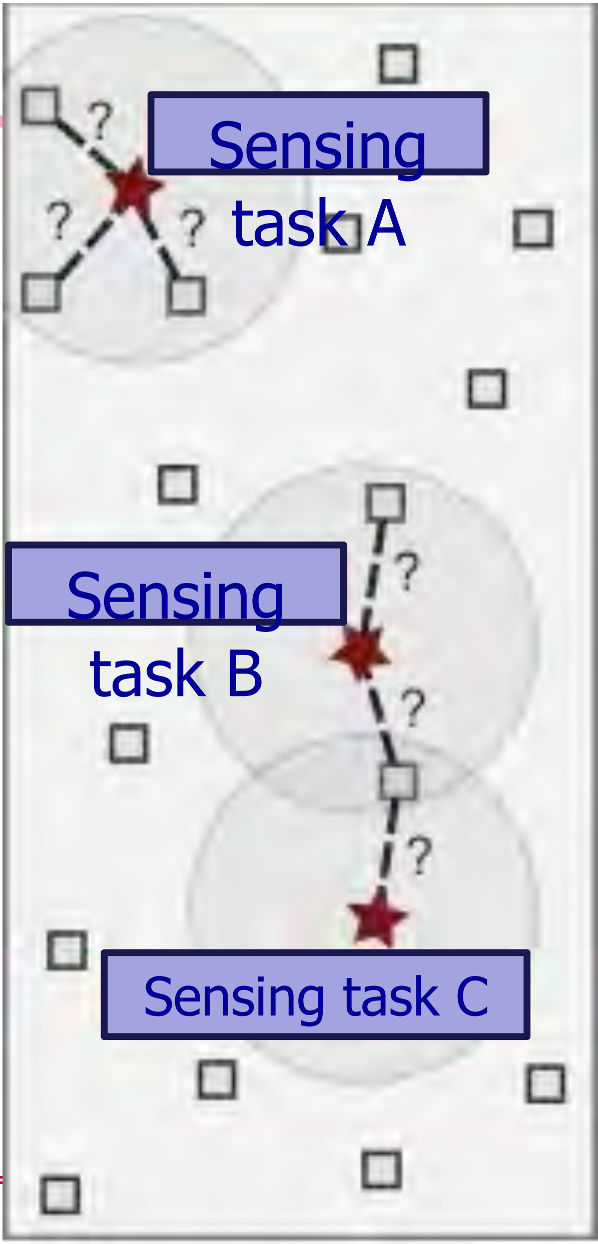


Self-adaptive behaviour: nodes experiencing energy peaks are selected with higher priority as next hop relays

Task allocation

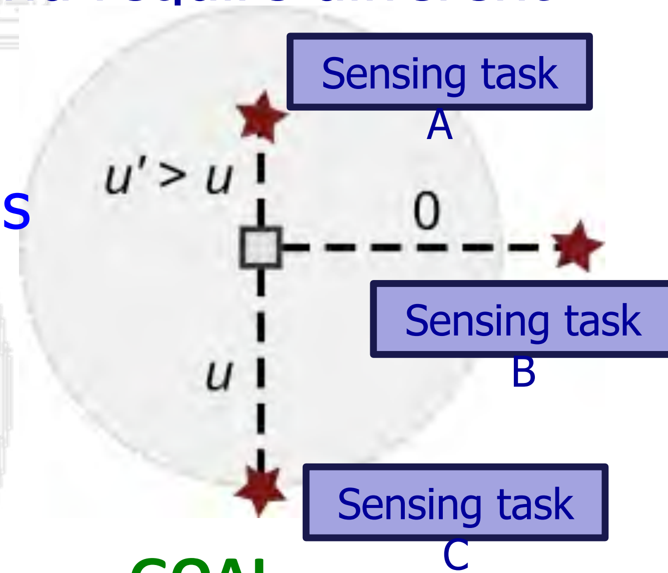
- Sensing tasks (missions) arrive in the network dynamically over time at different locations
- Multiple missions active at the same time, competing for the sensing resources of the network

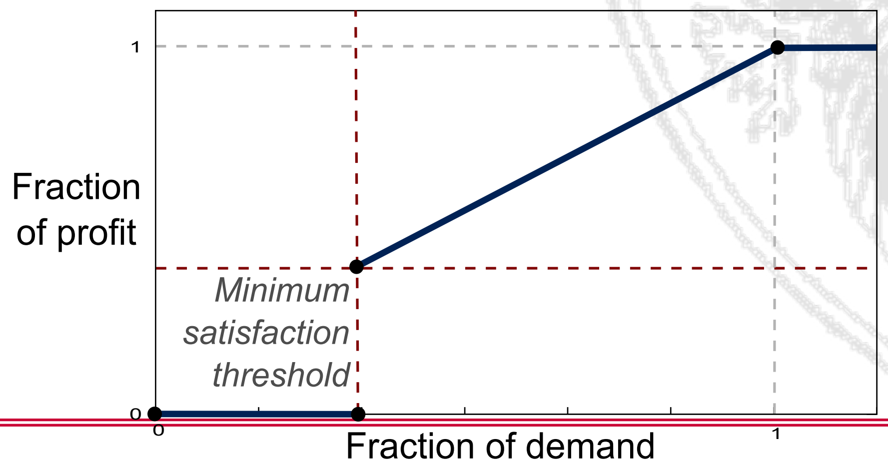
Decide which sensor(s) should be assigned to each mission



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

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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

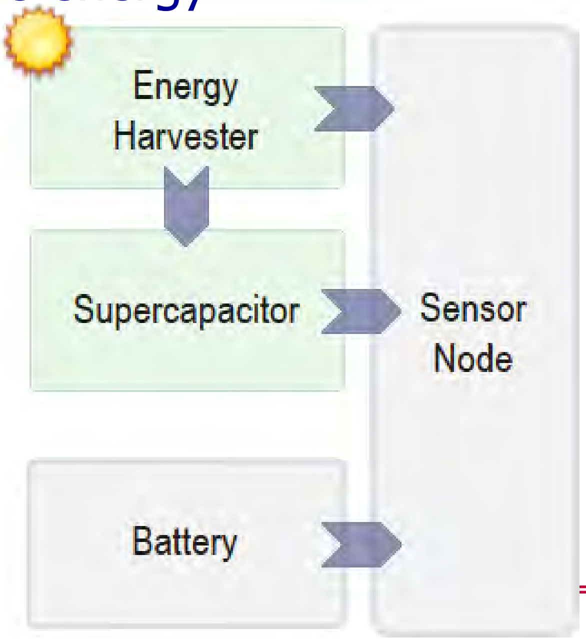
A **decentralized** harvesting-aware heuristic

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

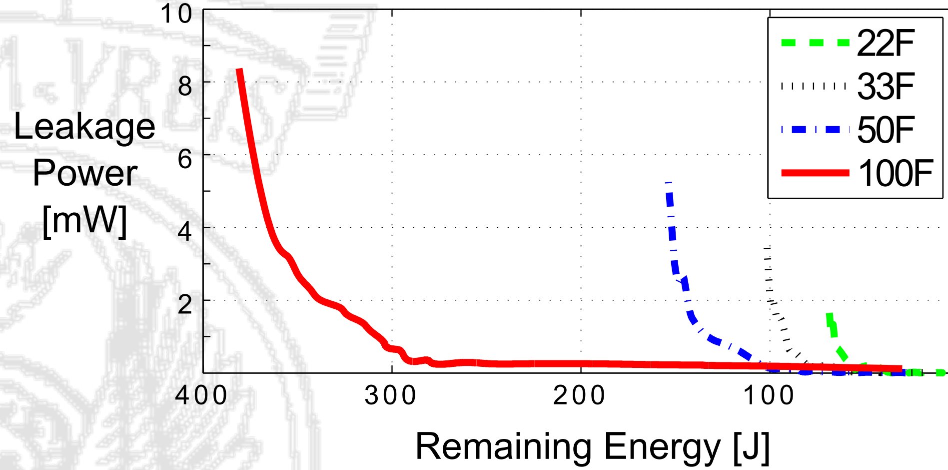
1. **Free:** fully sustained by harvesting
2. **Recoverable:** sustained by supercapacitor and recovered before next mission
3. **Capacitor-sustainable:** sustained by supercapacitor
4. **Battery-required:** sustained by battery



Modeling real harvesting systems

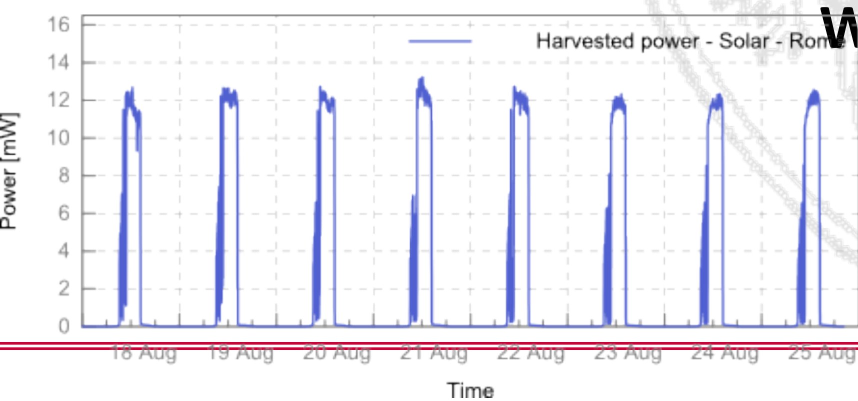
Non-ideal supercapacitors

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

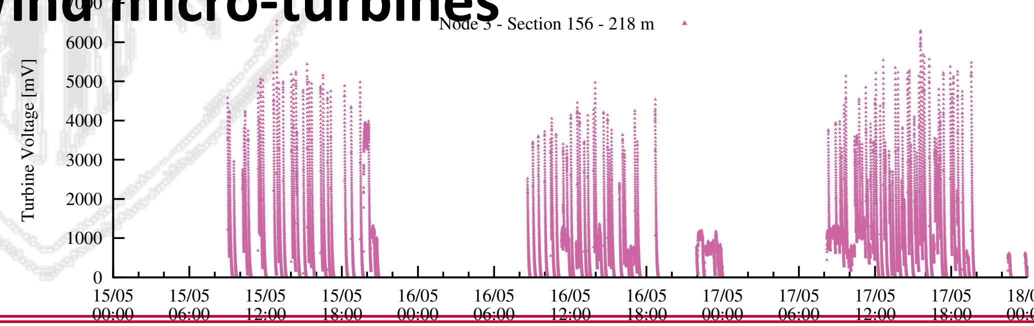


Real-life energy traces

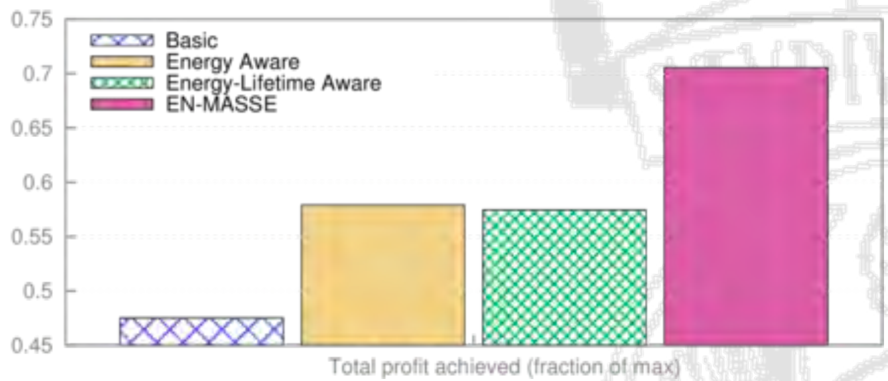
Photovoltaic cells

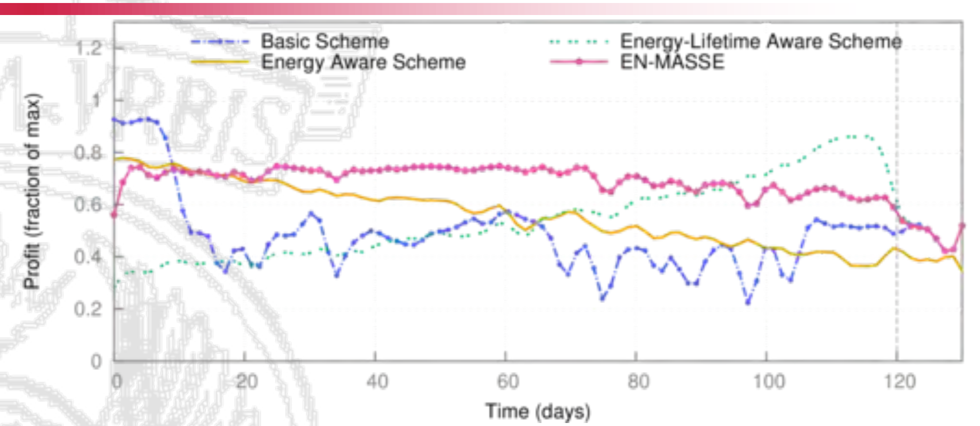


Wind micro-turbines



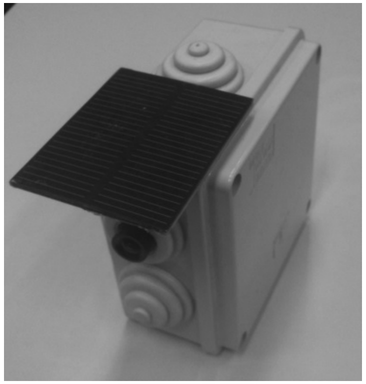
Performance evaluation

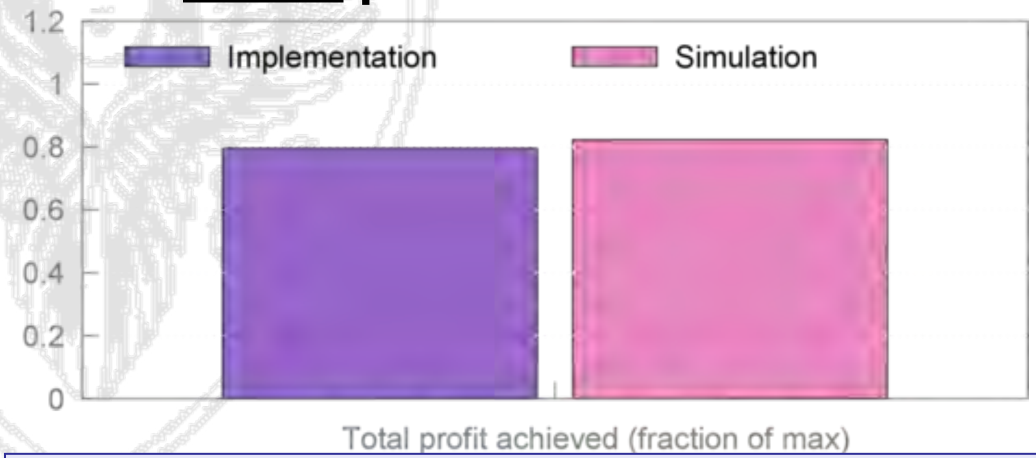




Profit: up to 60% higher than SoA

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





In-field testbed validation

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

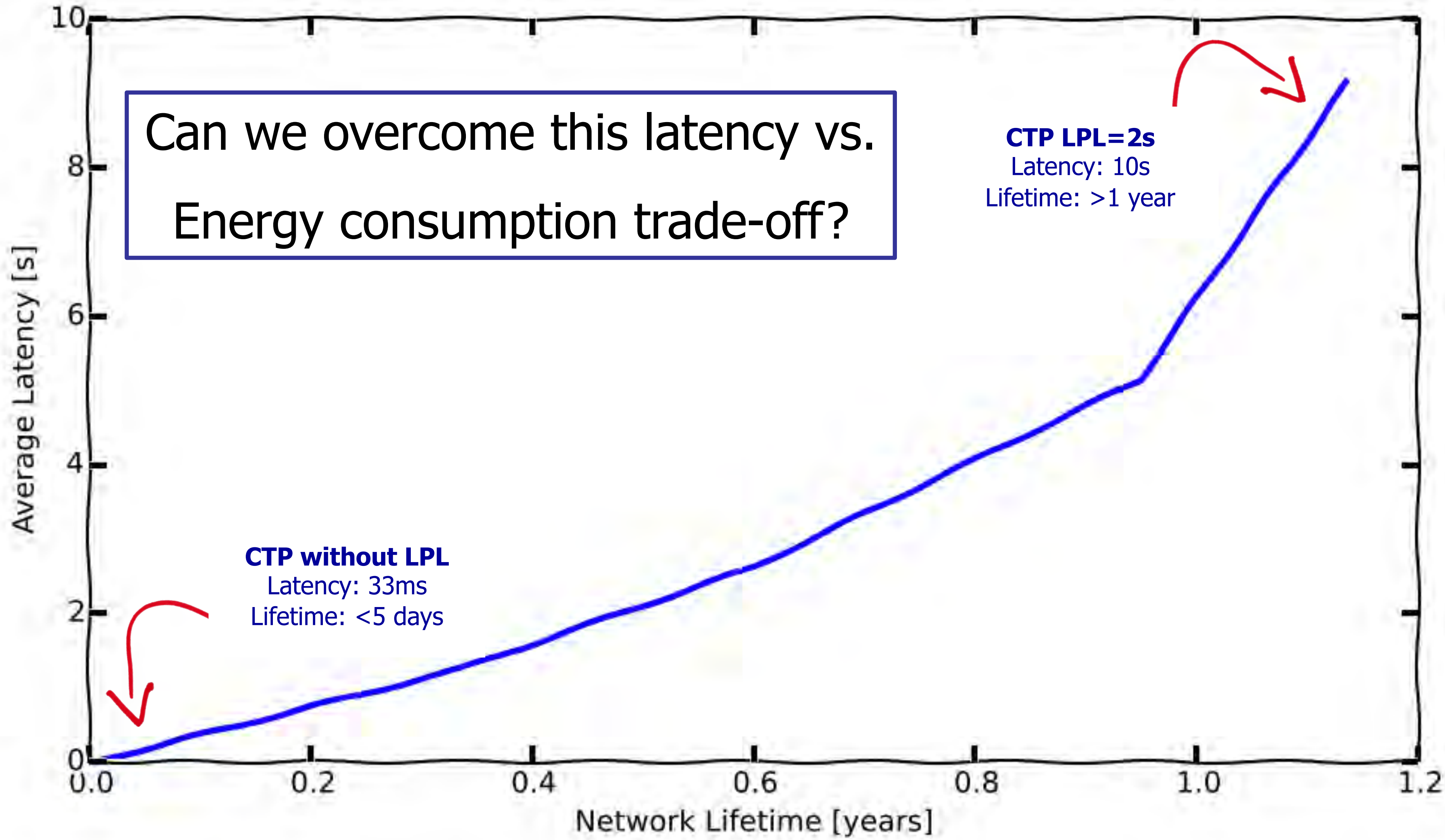
Protocols for wake-up radio enabled Internet of Things, a.a. 2020/2021

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

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

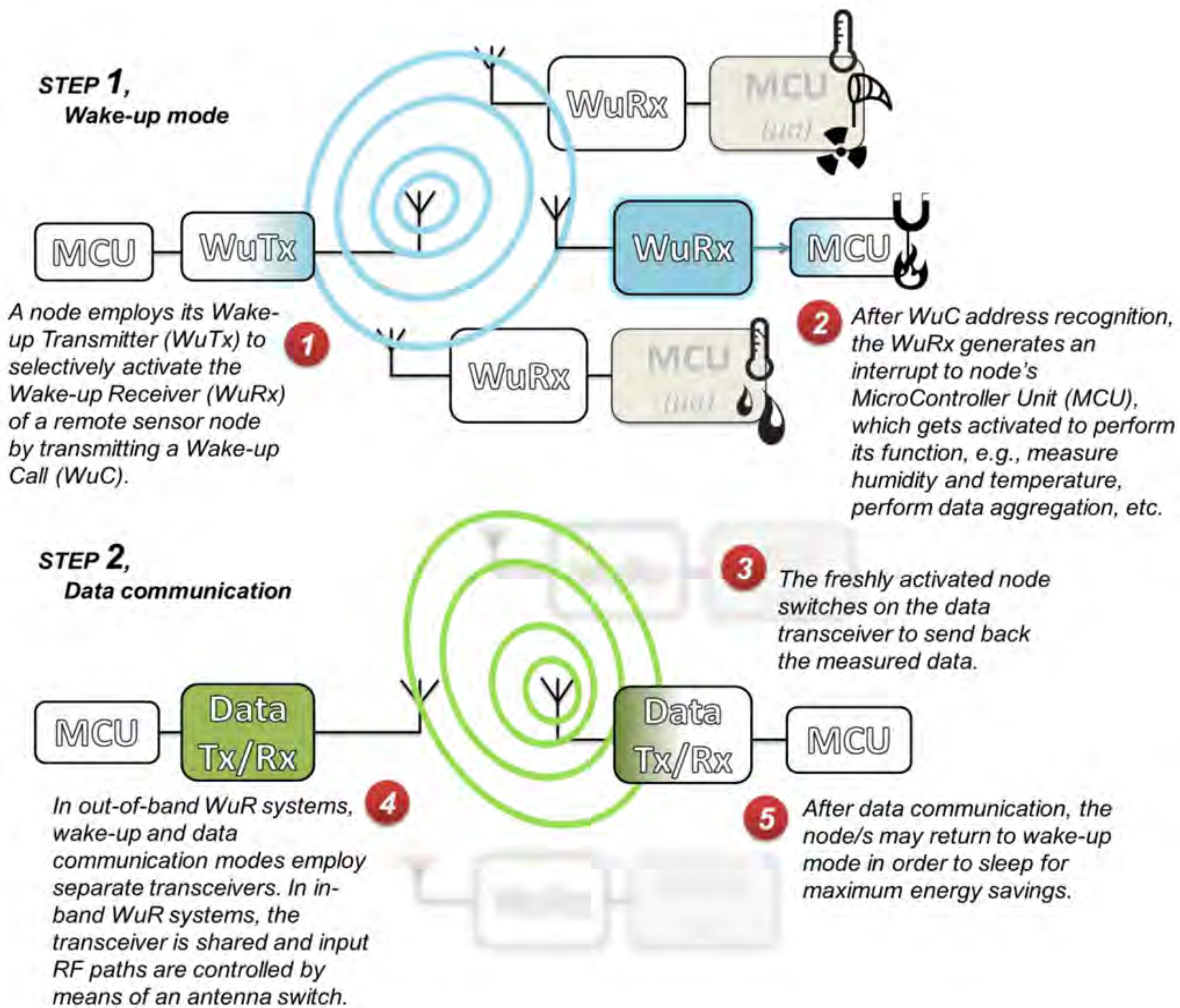
Latency vs. Energy Trade-off



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

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

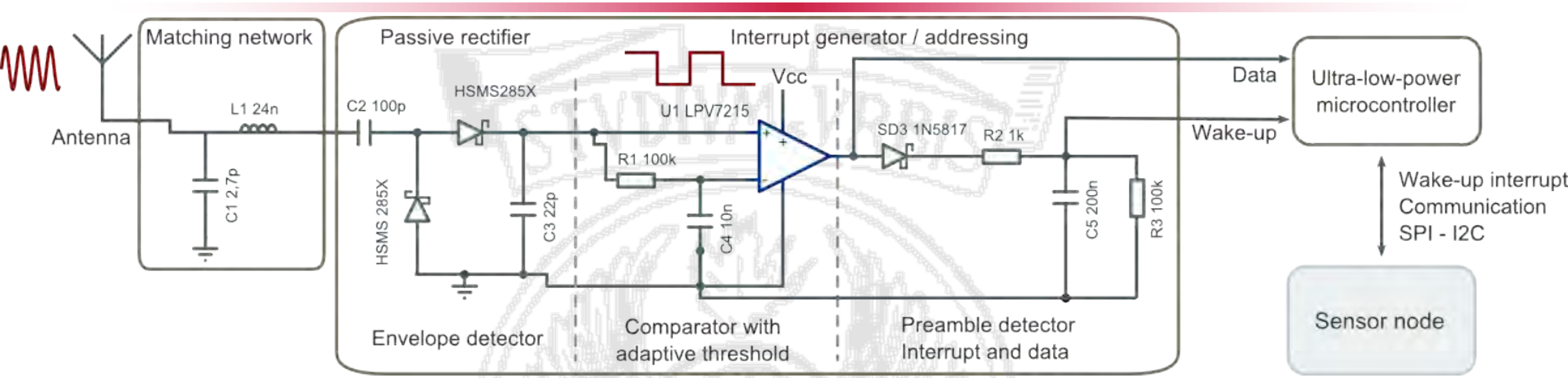
Semi-active WURs

- 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

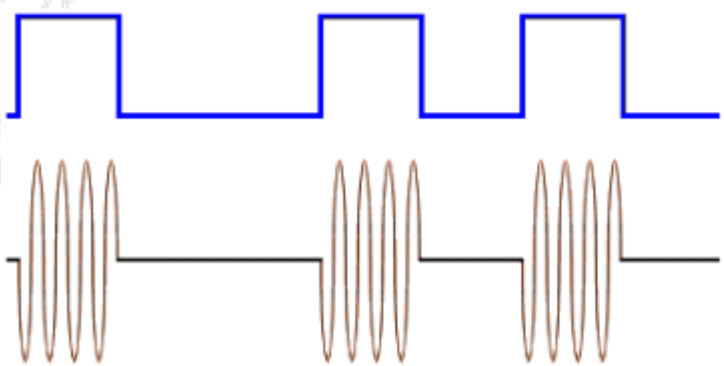
- Power consumption: 98-270 nW
- Wake-up range <= 10m

Our wake-up radio architecture

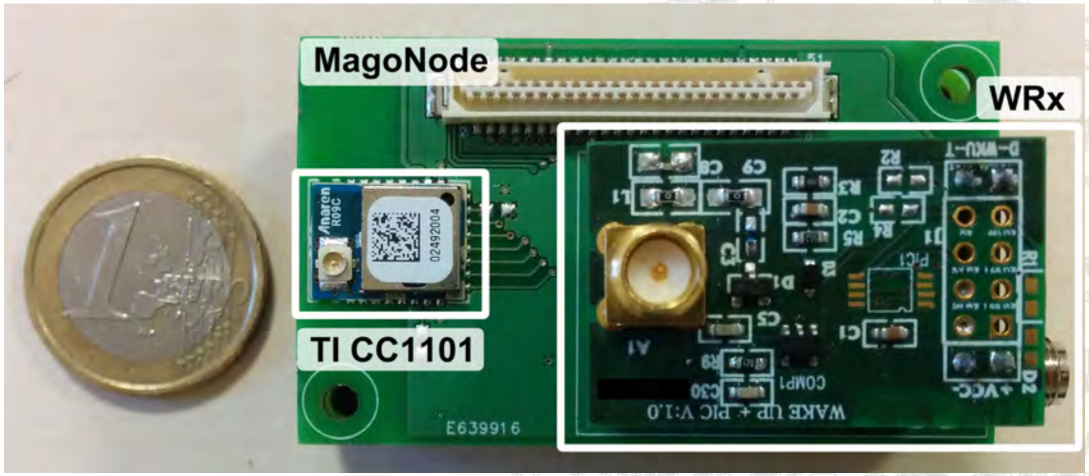


Collaboration with L. Benini and M. Magno, ETHZ

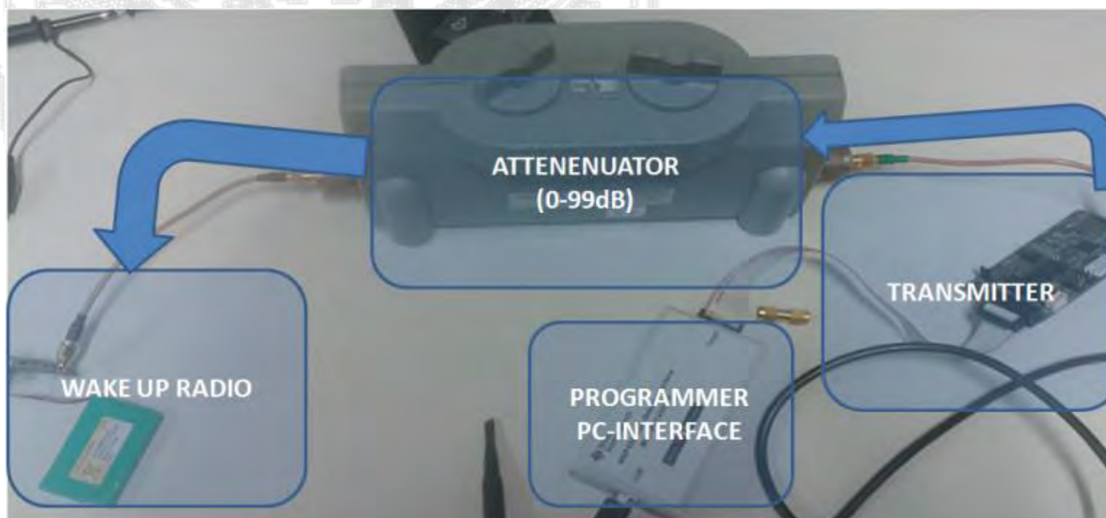
- OOK modulation
- Very low power consumption (< 1.3uW)
- High sensitivity (up to -49dBm)
- Fast reactivity (wake-up time of 130us)
- **Selective addressing**



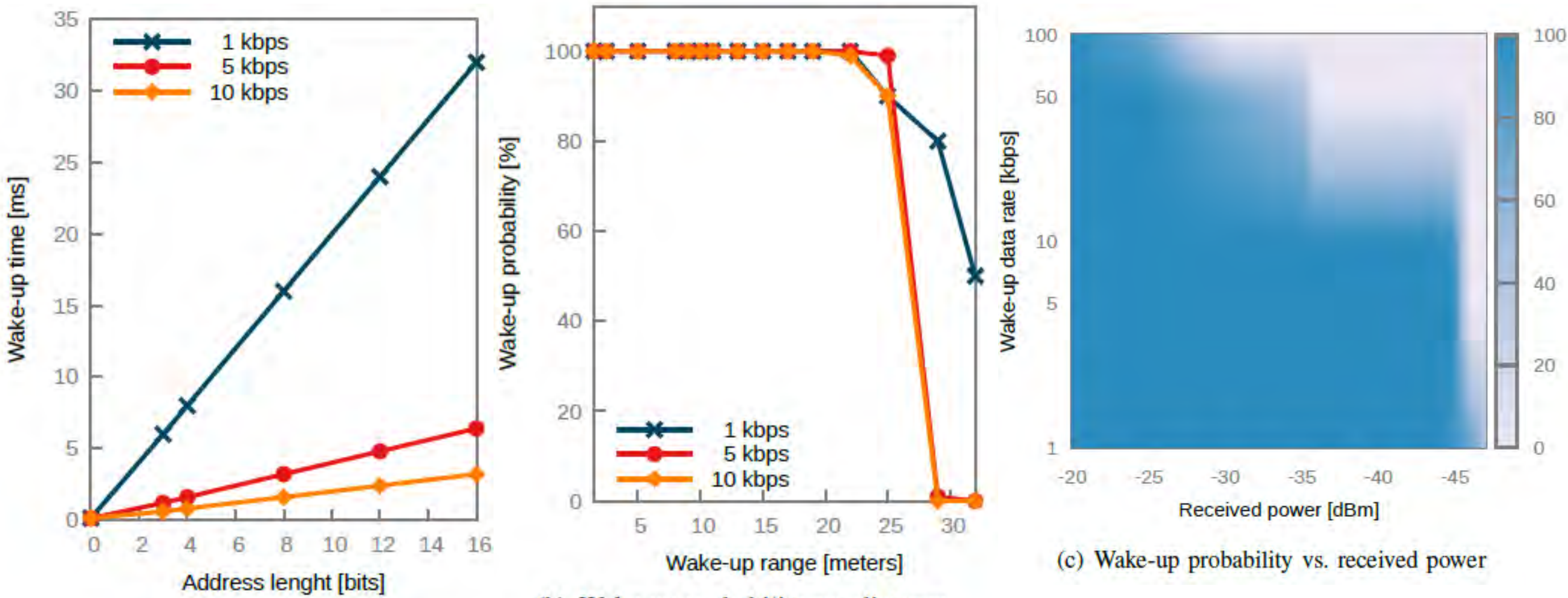
WRx prototyping and testing



- 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

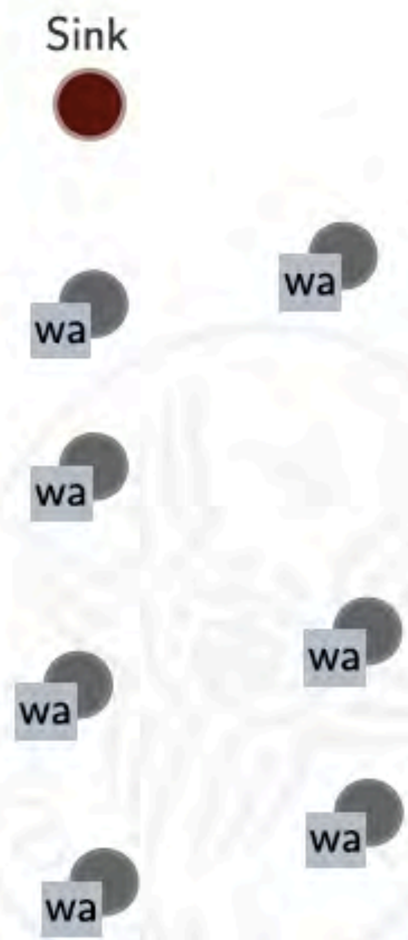
- Exploits proposed WuR to addresses latency vs. energy consumption tradeoff
- Both interest dissemination and convergecasting primitives
- **Key idea**: use wake-up addresses to wake up a node or a group of nodes based on certain properties

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 $= w_a$



FLOOD-WUP

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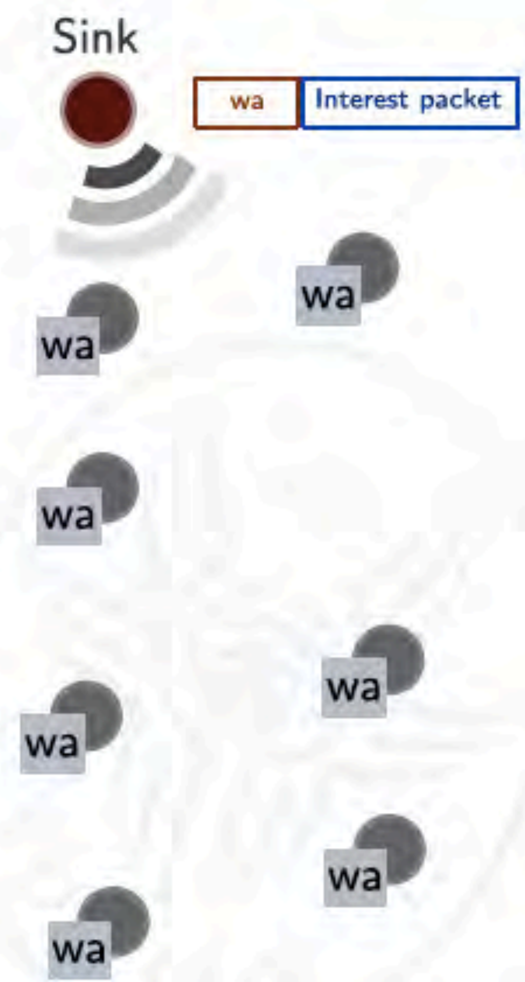
- Sink broadcasts first interest packet preceding it with wake-up sequence w_a



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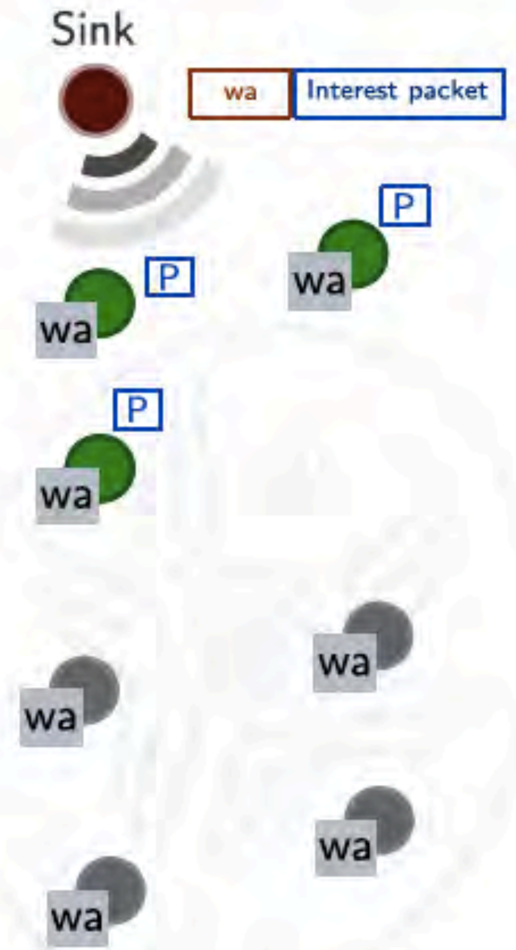

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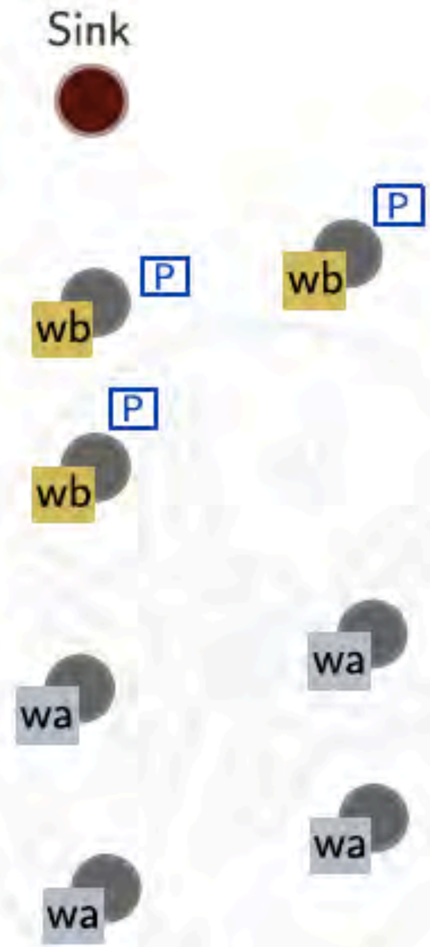
- Nodes with address w_a wakes up, sets main radio to RX, receive packet
- Then change broadcast wake-up address to w_b



Flood-WUP

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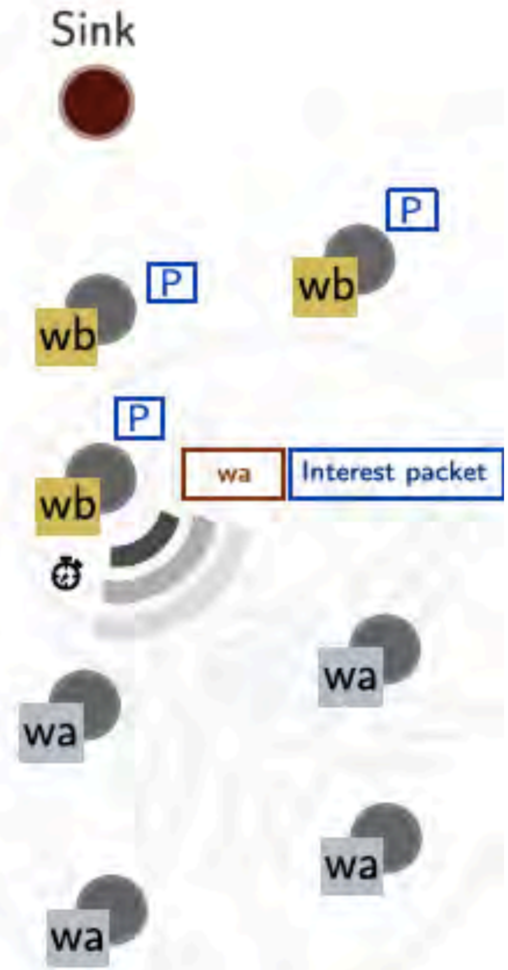
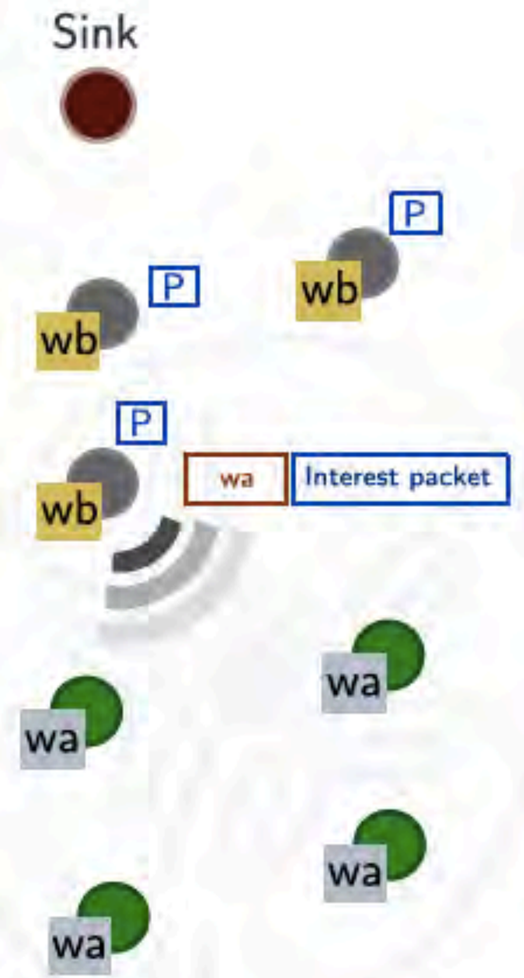
- Then change broadcast wake-up address to w_b
- After a random time, nodes re-broadcast packet preceding it with w_a



Flood-WUP

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**



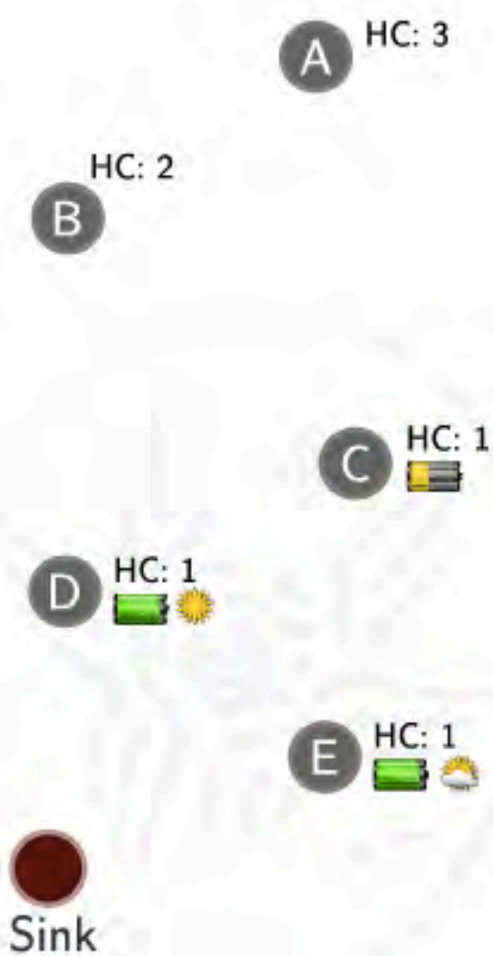
Converge Casting: GREEN-WUP

- 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 $\leq T_{high}$
0	battery level $\leq T_{low}$



GREEN-WUP

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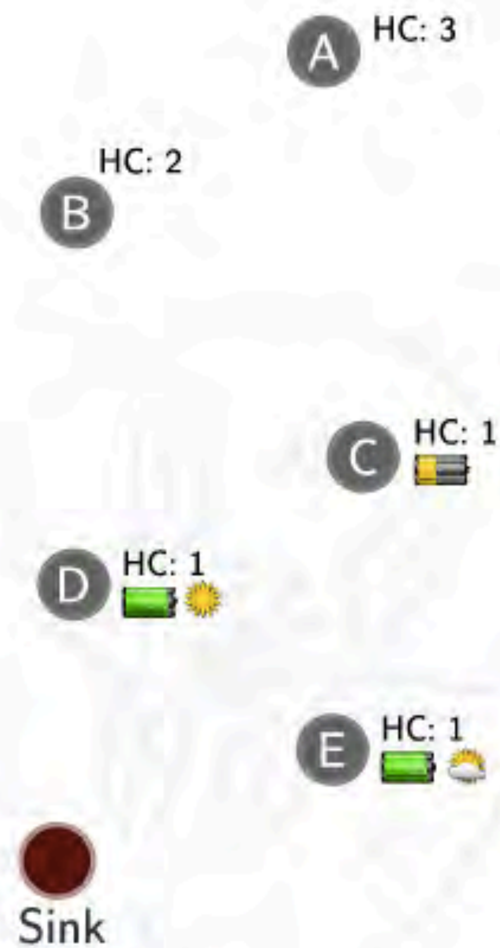
- Node B has a packet to transmit



GREEN-WUP

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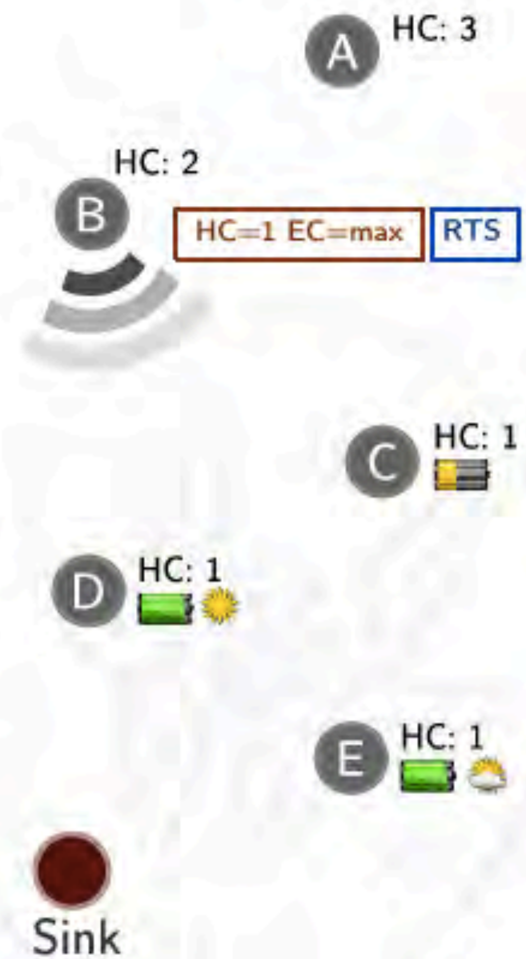
- Node B has a packet to transmit
- Sends RTS only to nodes with hopcount = 1 and energy = max. Then it goes to sleep



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- Node B has a packet to transmit
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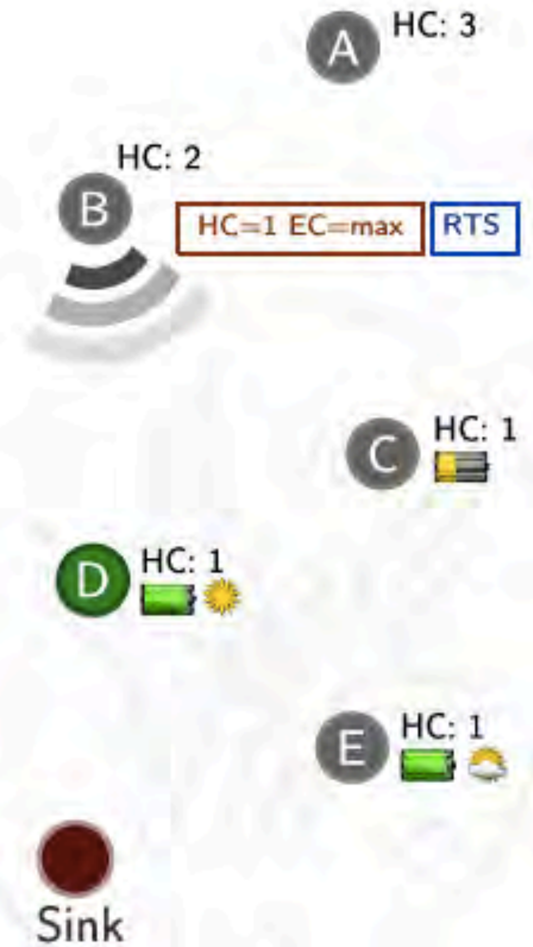
- Only node D wakes up. Other nodes continues to sleep



GREEN-WUP

- Example: energy classes

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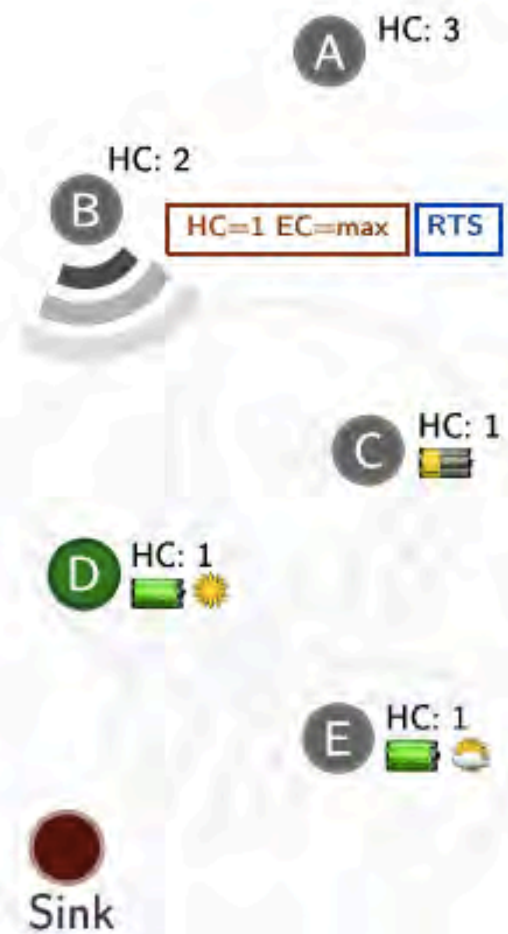
- Only node D wakes up. Other nodes continues to sleep
- Iterate on energy class if no relay found



GREEN-WUP

- Example: energy classes

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- Node B has a packet to transmit
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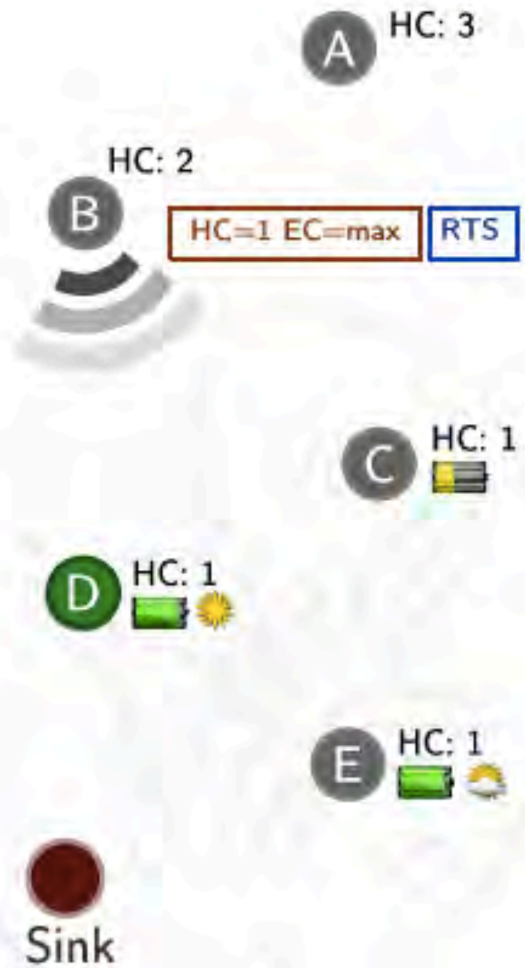
- Only node D wakes up. Other nodes continues to sleep
- Iterate on energy class if no relay found
- CTS, DATA, ACK..



SAPIENZA
UNIVERSITÀ DI ROMA

Sim. scenario

Different concept of wake up radio

- Active, higher energy consumption

+ Semantic WUP radio addresses

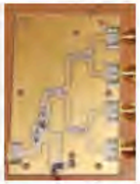
+ Only one transceiver (TX)

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)

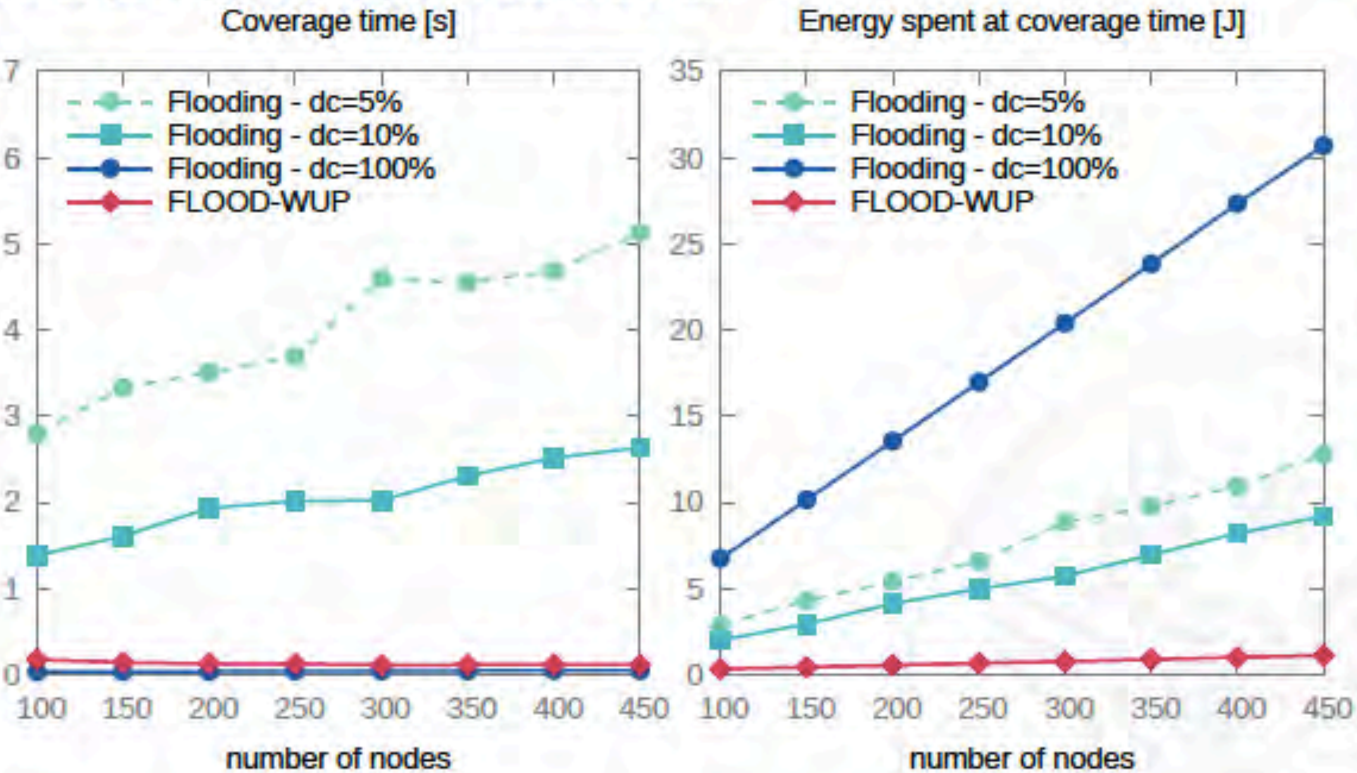


Green Castalia simulations

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

Perf. Evaluation

FLOOD-WUP, 100-450 nodes



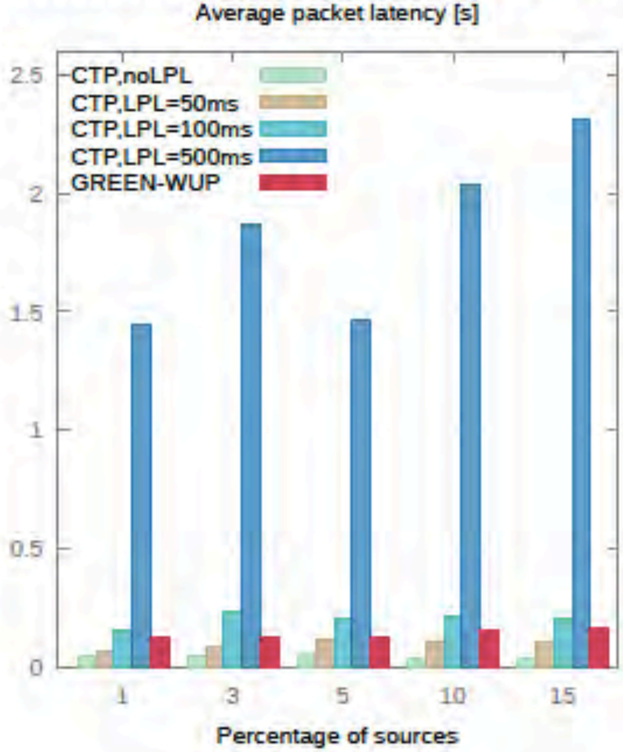
Coverage time similar to Flooding with 100% DC

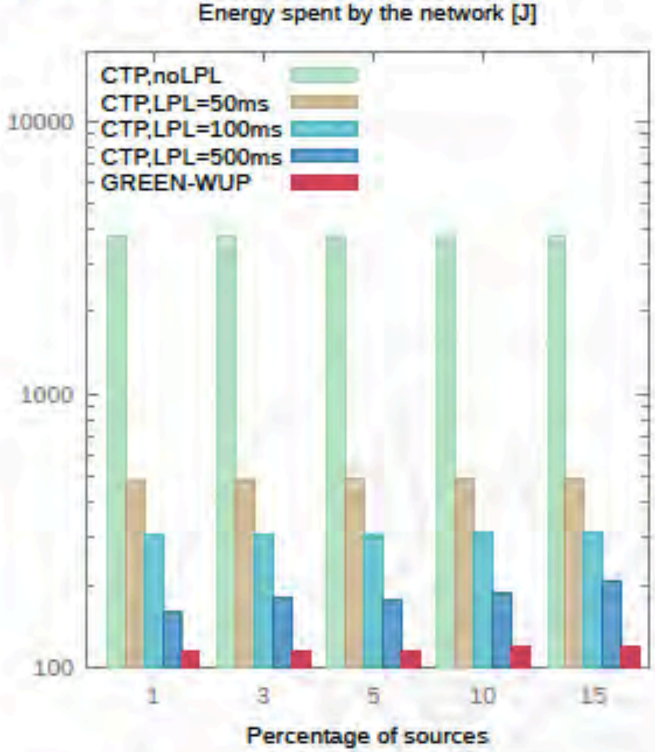
Energy consumption reduced of up to ≈ 96%

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

Perf. Evaluation

GREEN-WUP, network of 100 nodes



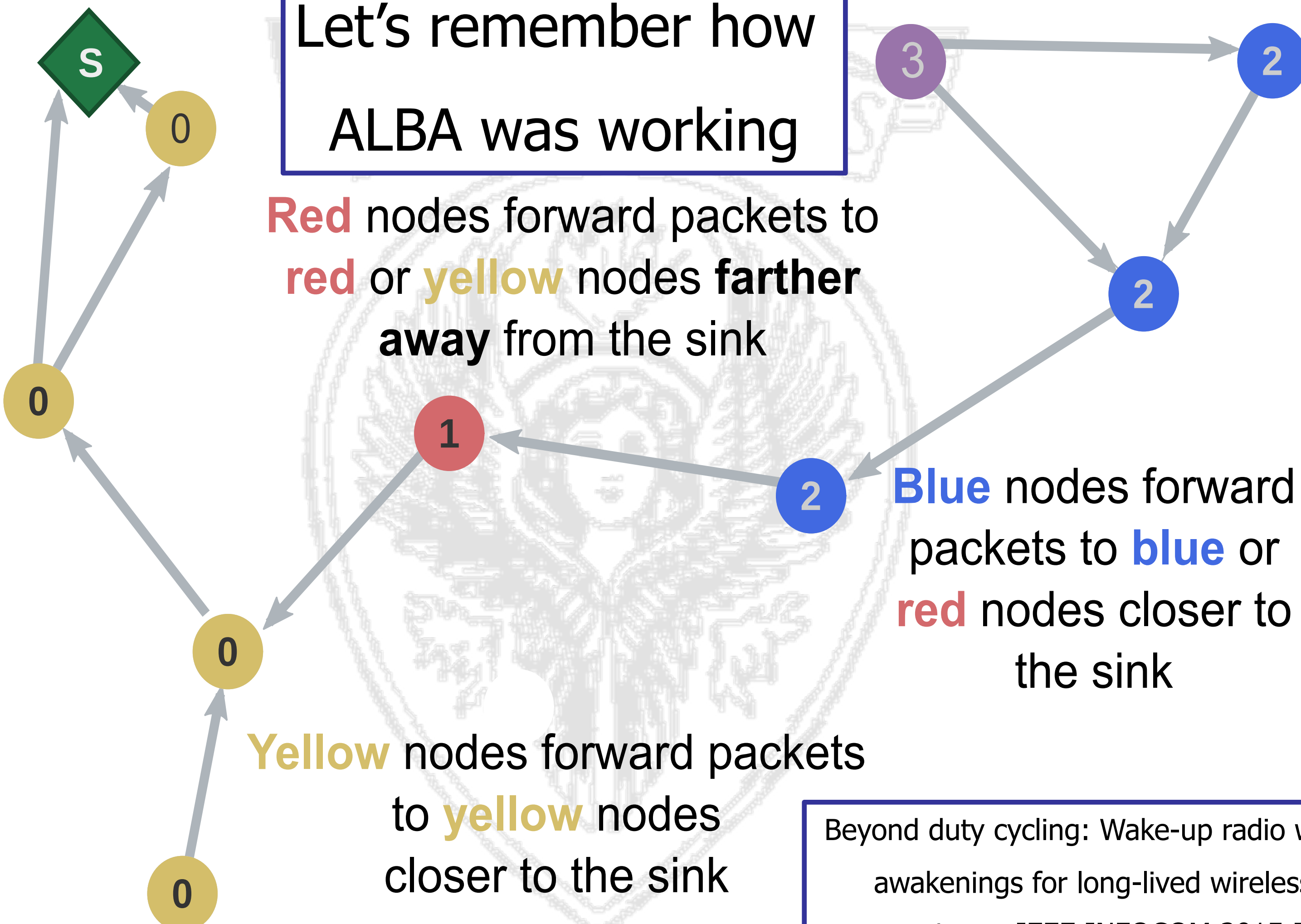


Average latency 100 ms higher than CTP without LPL

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

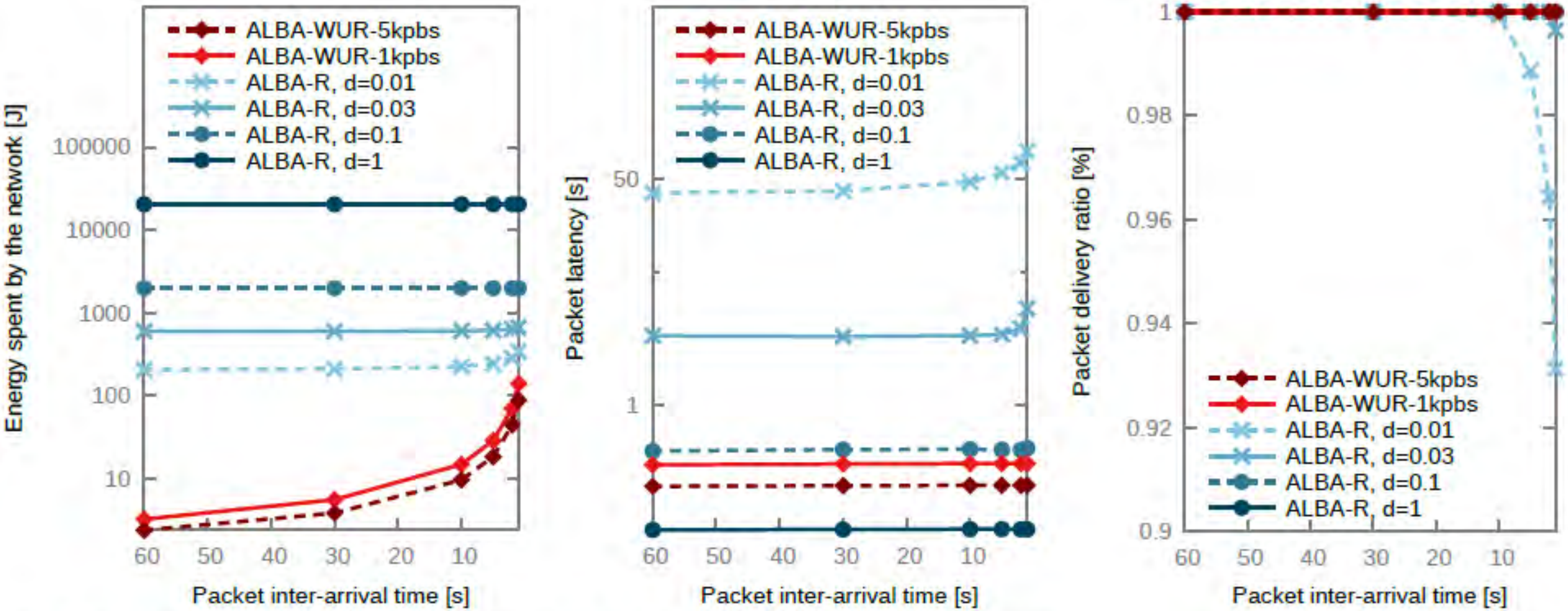
Yellow nodes forward packets to **yellow** nodes closer to the sink

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

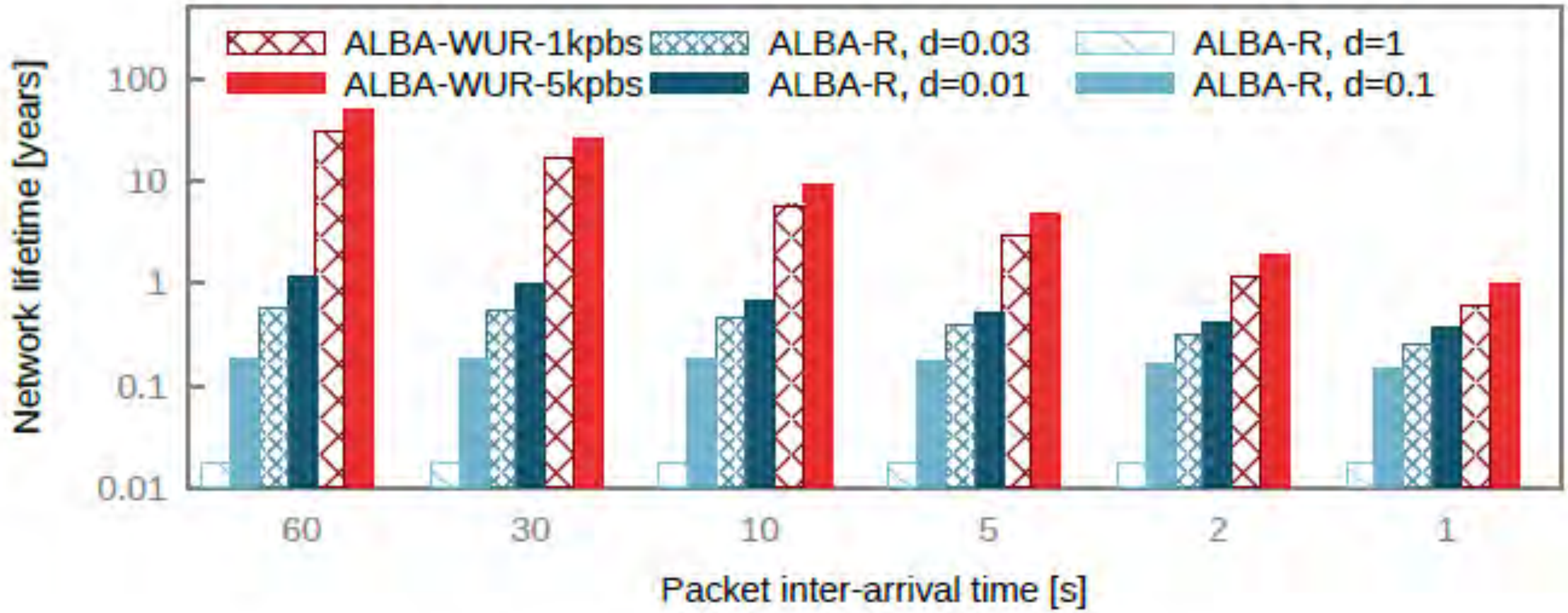


Fig. 5. Network lifetime (the y axis is logscale).

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