Protocols for EH-WSNs

Internet of Things, a.a. 2019/2020

Un. of Rome "La Sapienza"

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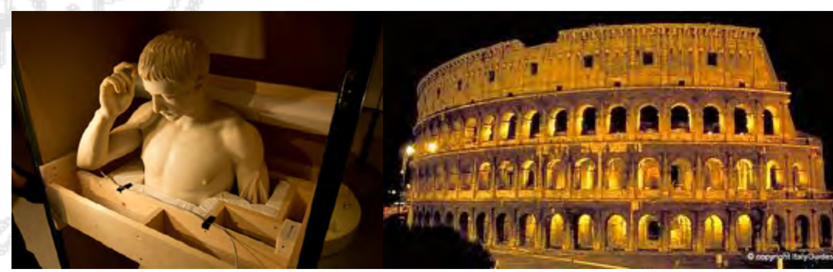
Application scenarios

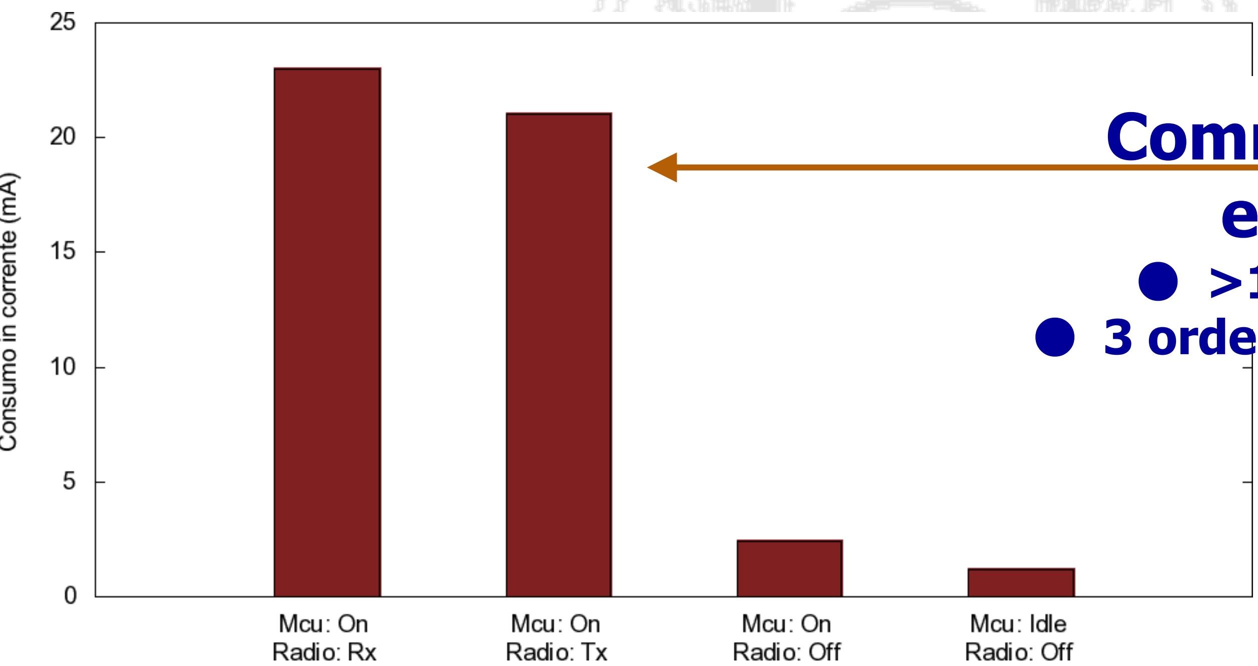
Structural health monitoring



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)

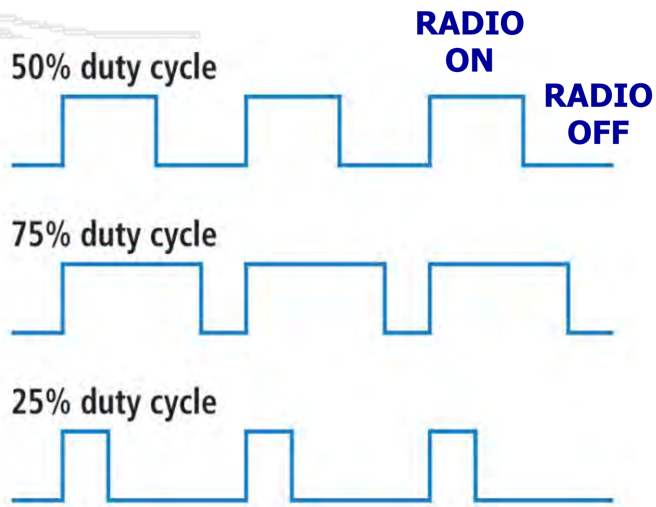


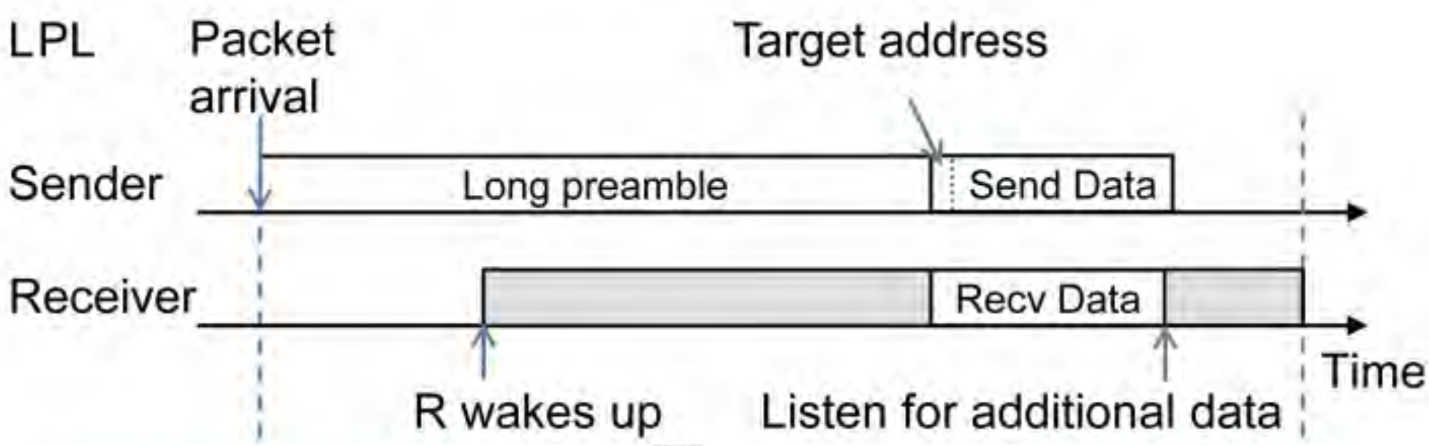
Communication is expensive!

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

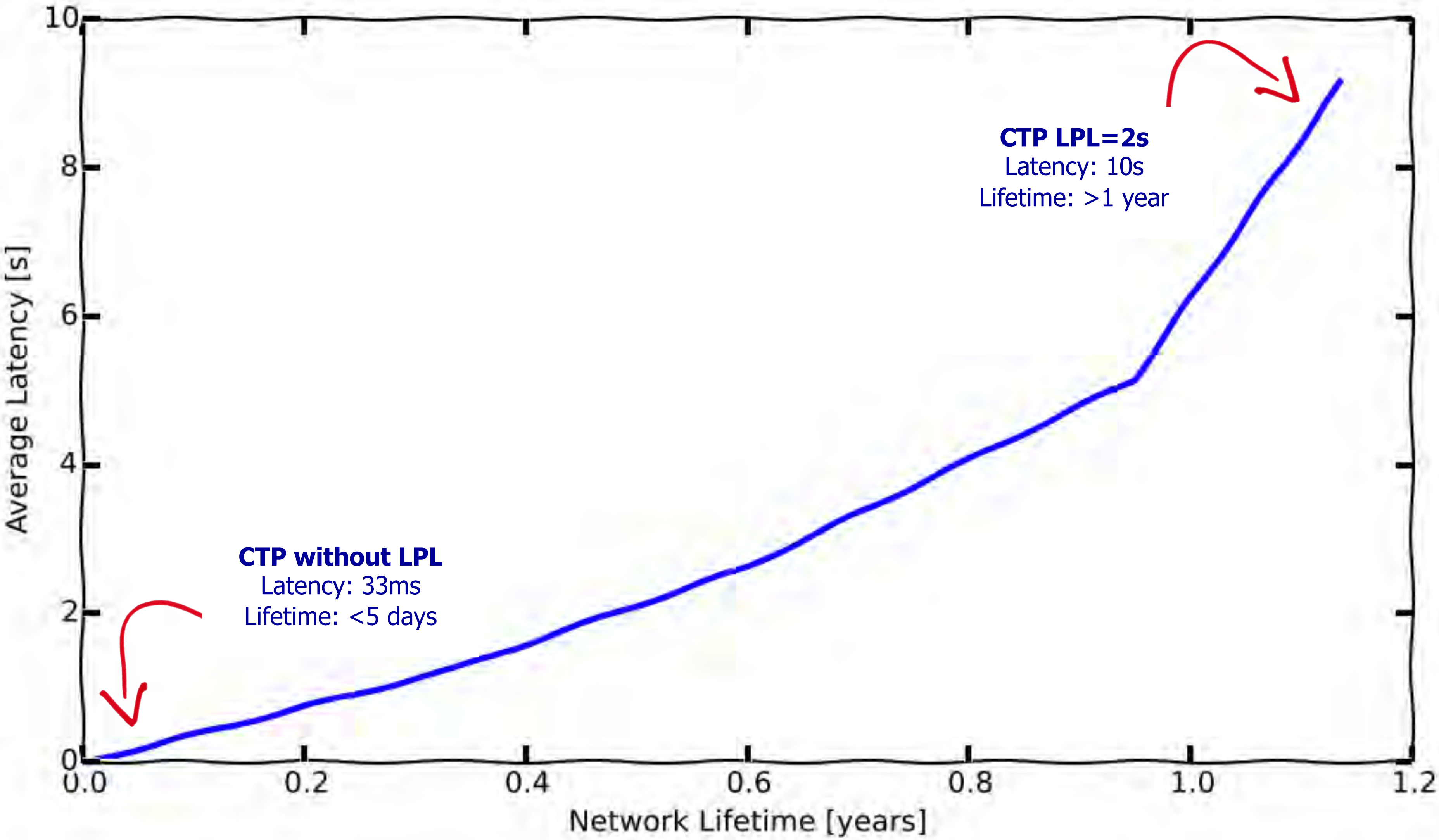
Standard Approach: Duty Cycling

- 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



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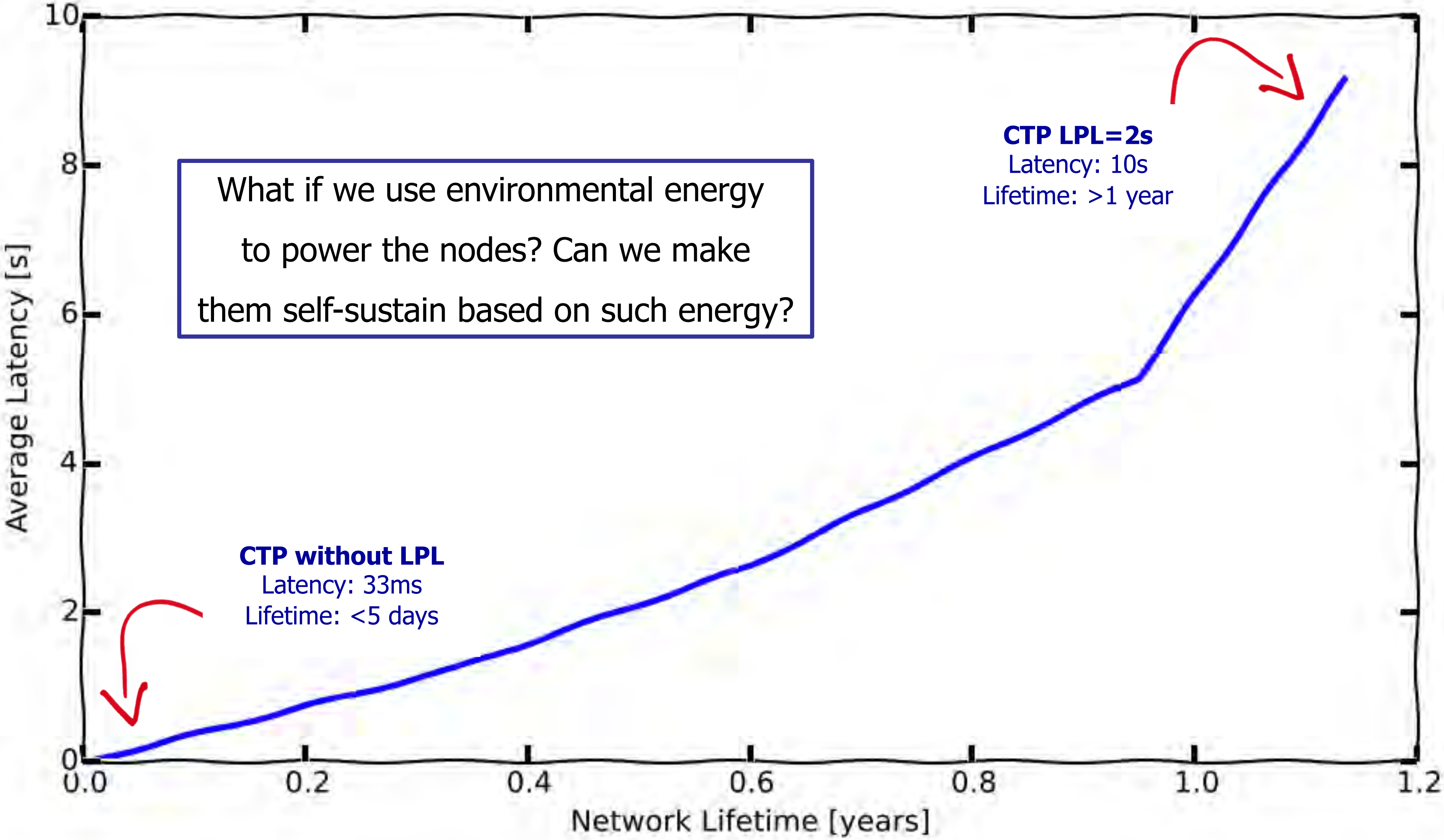
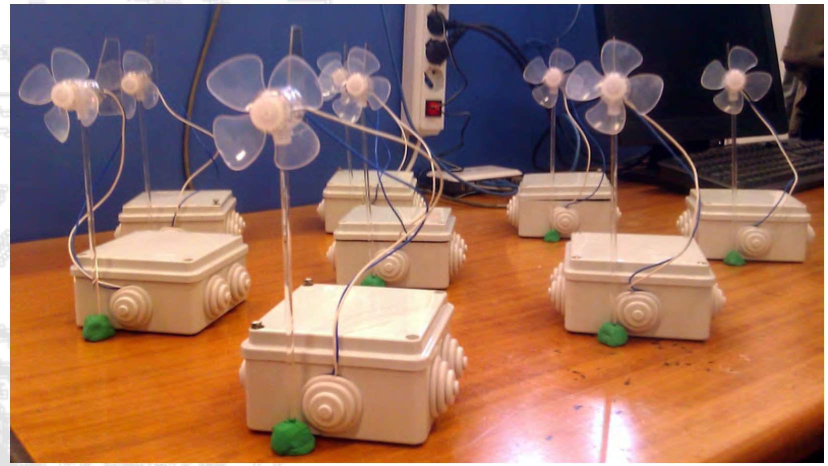


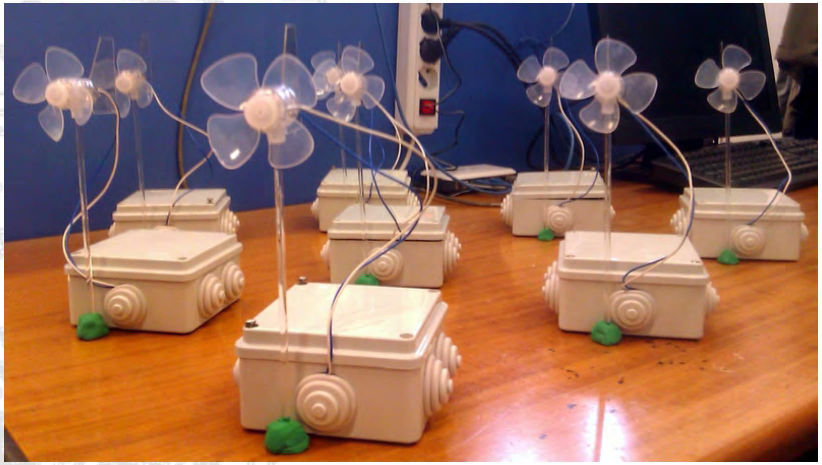
What if we use environmental energy to power the nodes? Can we make them self-sustain based on such energy?

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



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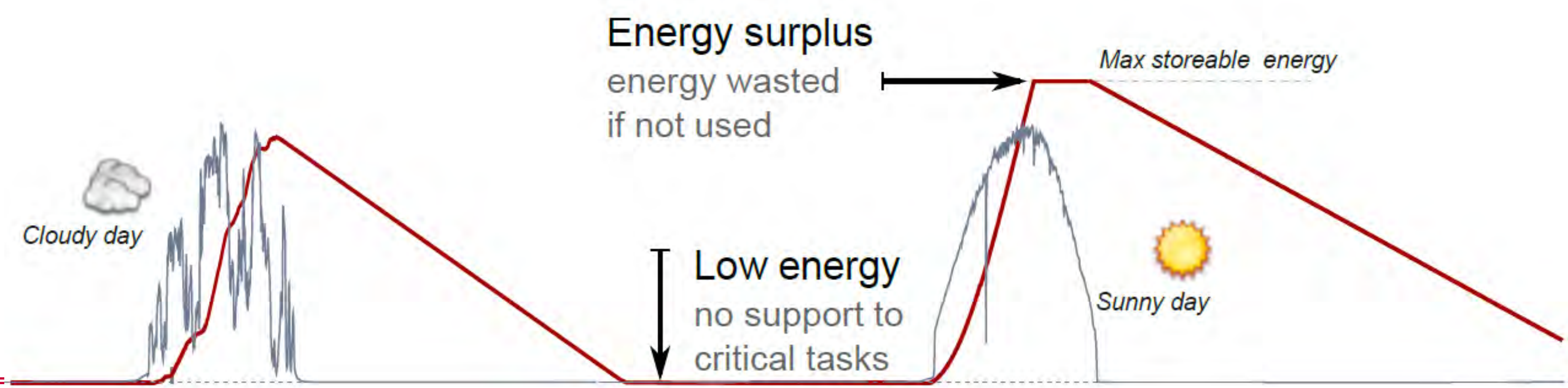
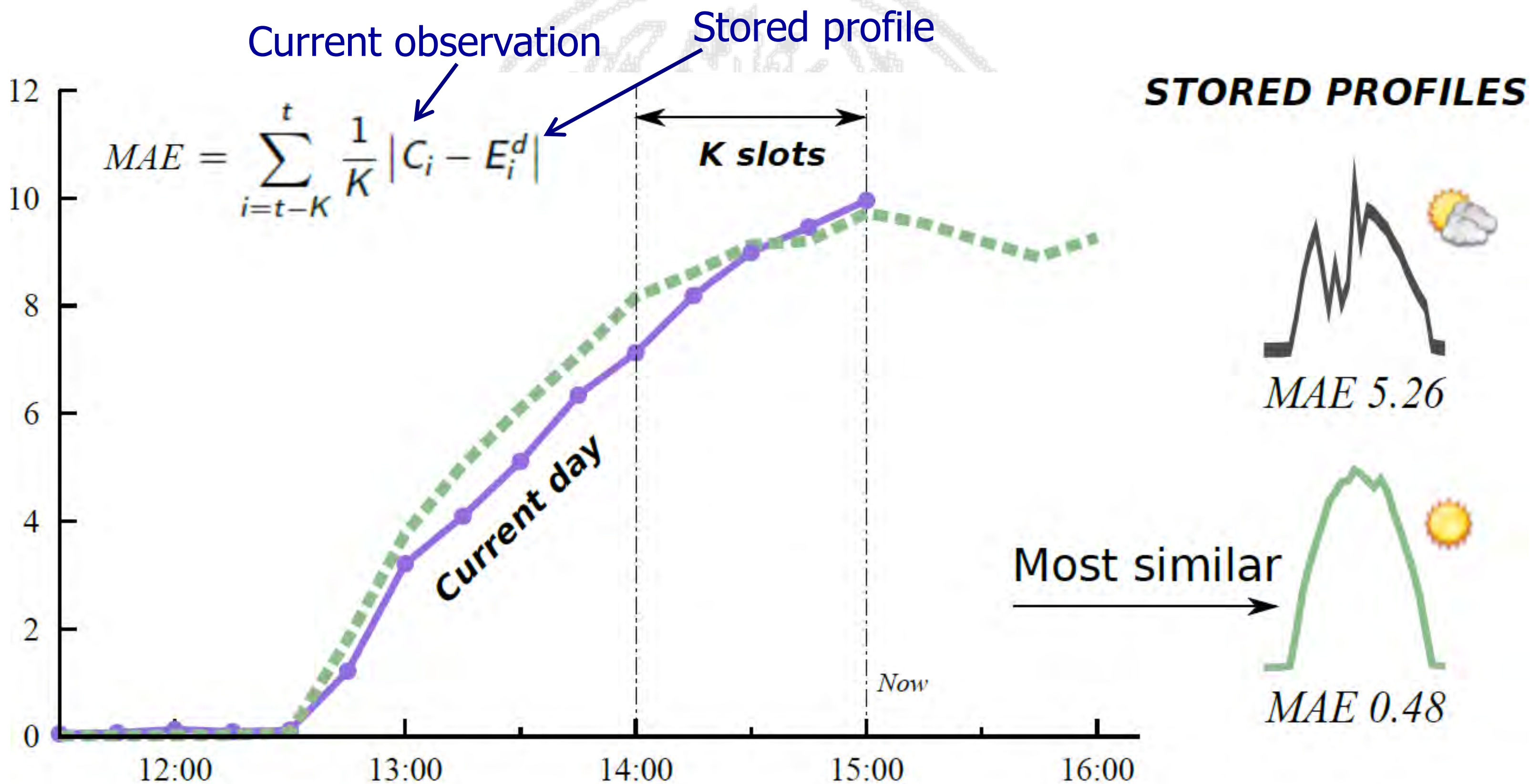
Why energy predictions?

- 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



Examples of profiles

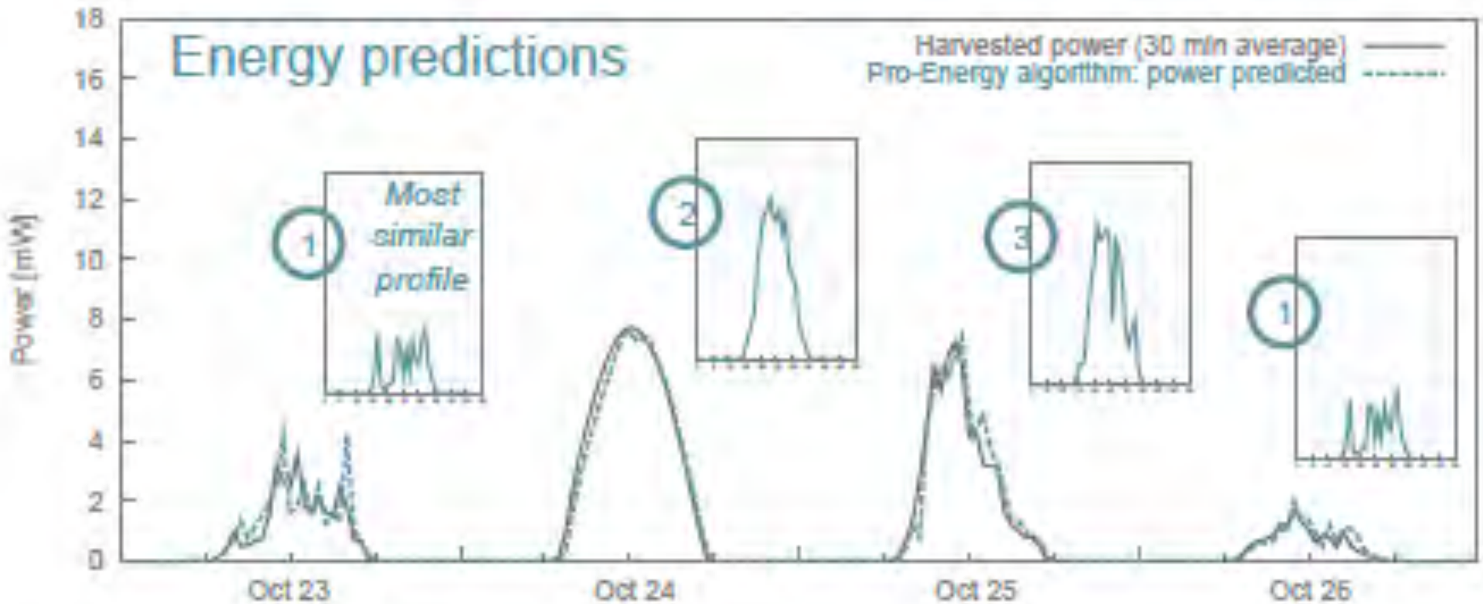


Figure 1. Pro-Energy: harvesting profiles representing energy observations from past days are used to predict the future energy availability.

How to select the current D profiles?

How to predict based on most similar profile?

Pro-Energy in a nutshell

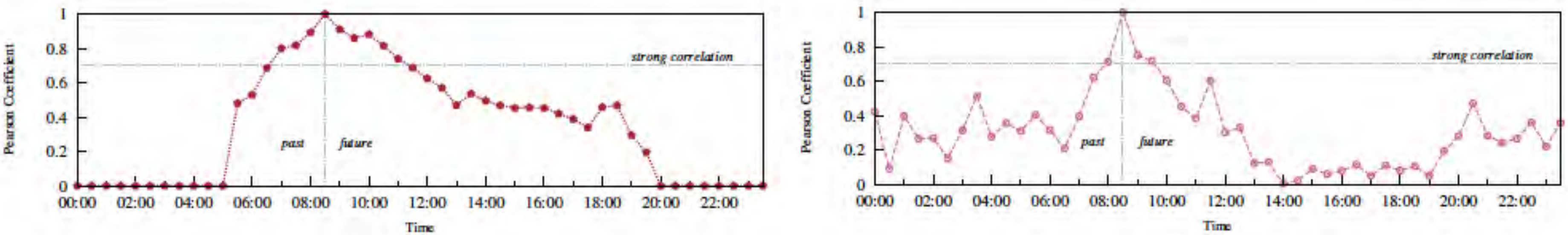
$$\hat{E}_{t+1} = \alpha \cdot C_t \; + \; (1-\alpha) \cdot E^d_{t+1} \qquad (2)$$

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



(a) (b)

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

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

Stored profiles update

At the end of the day the profile P of the current day enters the pool if

- We have less than D profiles OR

-There are old profiles in the pool (stored longer than D_{th} days ago) OR

-There is a pair of profiles in the pool which are too similar (MAE below a threshold) →the new profile moves in, the most similar to it among the pairs too close to each other moves out from the pool

Combining multiple profiles

Let $E^{d_1}, E^{d_2}, \ldots, E^{d_P}$ be the ordered list of profiles that are most similar to the current day C, i.e., profiles with the smaller Mean Absolute Errors. The weighted profile WP, for the future slot $t+i$, $i \in \{1, 2, \ldots, F\}$, is computed as:

$$WP_{t+i} = \frac{1}{P-1} \sum_{j=0}^{P} w_j \cdot E_{t+i}^{d_j} \quad (4)$$

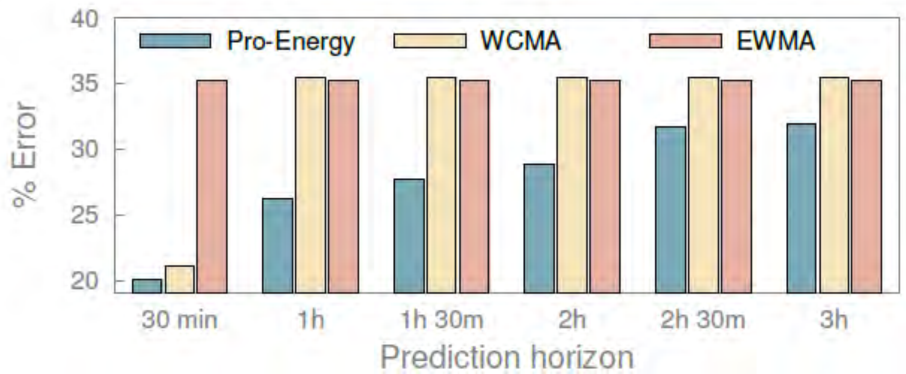
where

$$w_j = 1 - \frac{MAE_k(E^{d_j}, C)}{\sum_{j=1}^{P} MAE_k(E^{d_j}, C)} \quad (5)$$

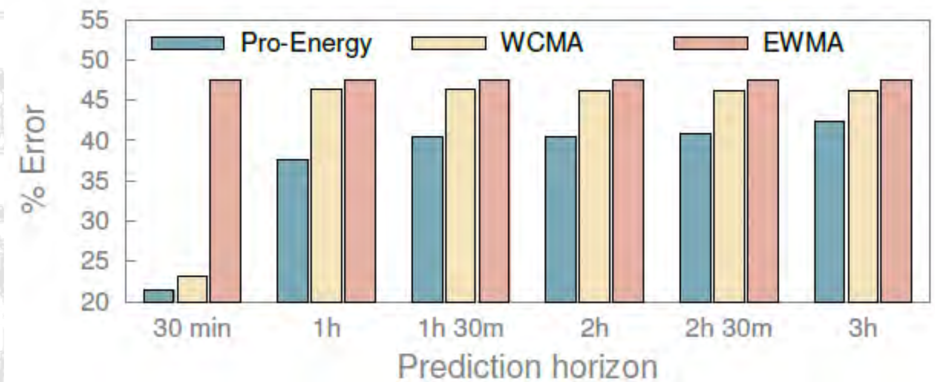
$$\hat{E}_{t+i} = \gamma_i \cdot C_t \ + \ (1 - \gamma_i) \cdot WP_{t+i}$$

Pro-Energy accuracy

Solar



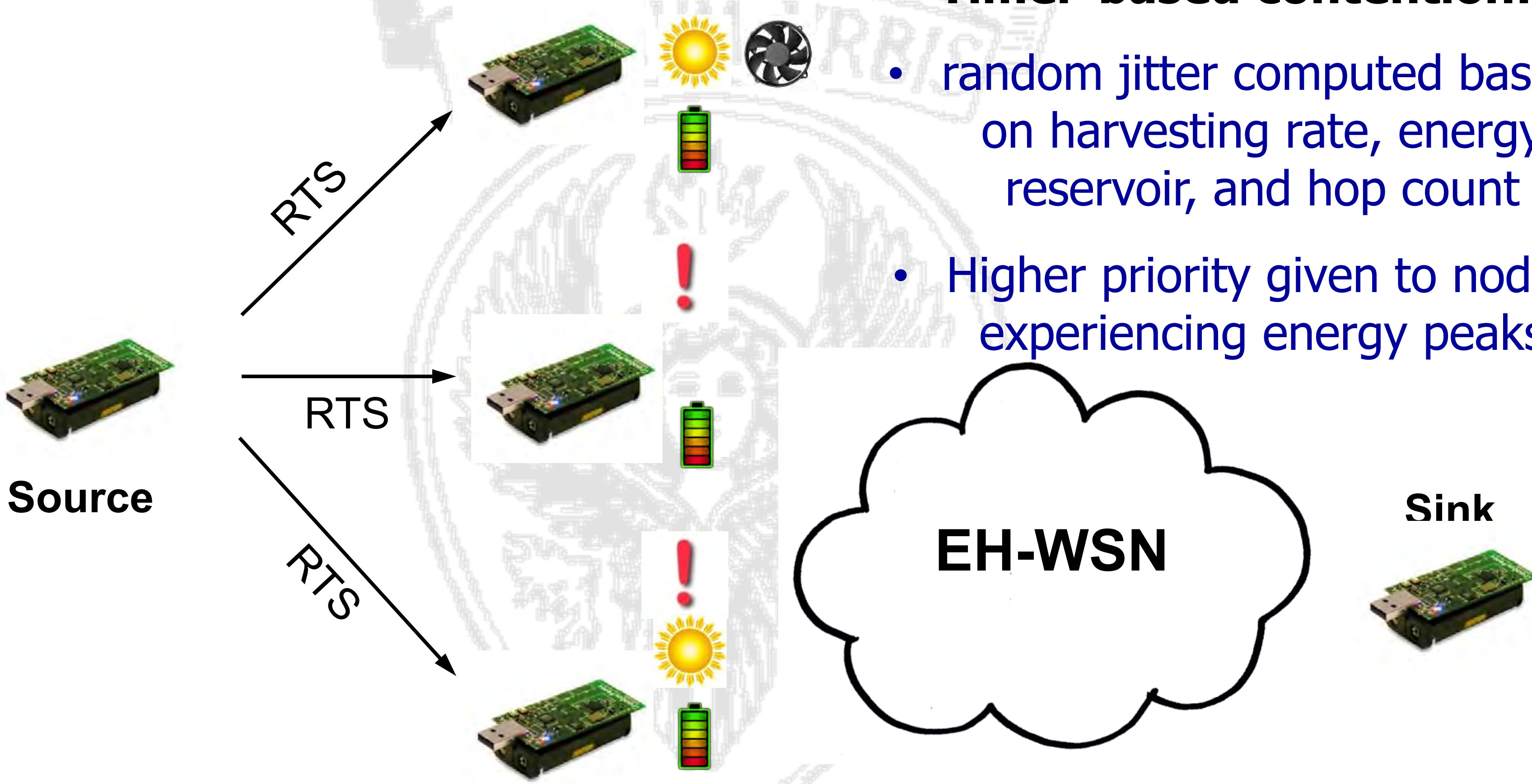
Wind



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

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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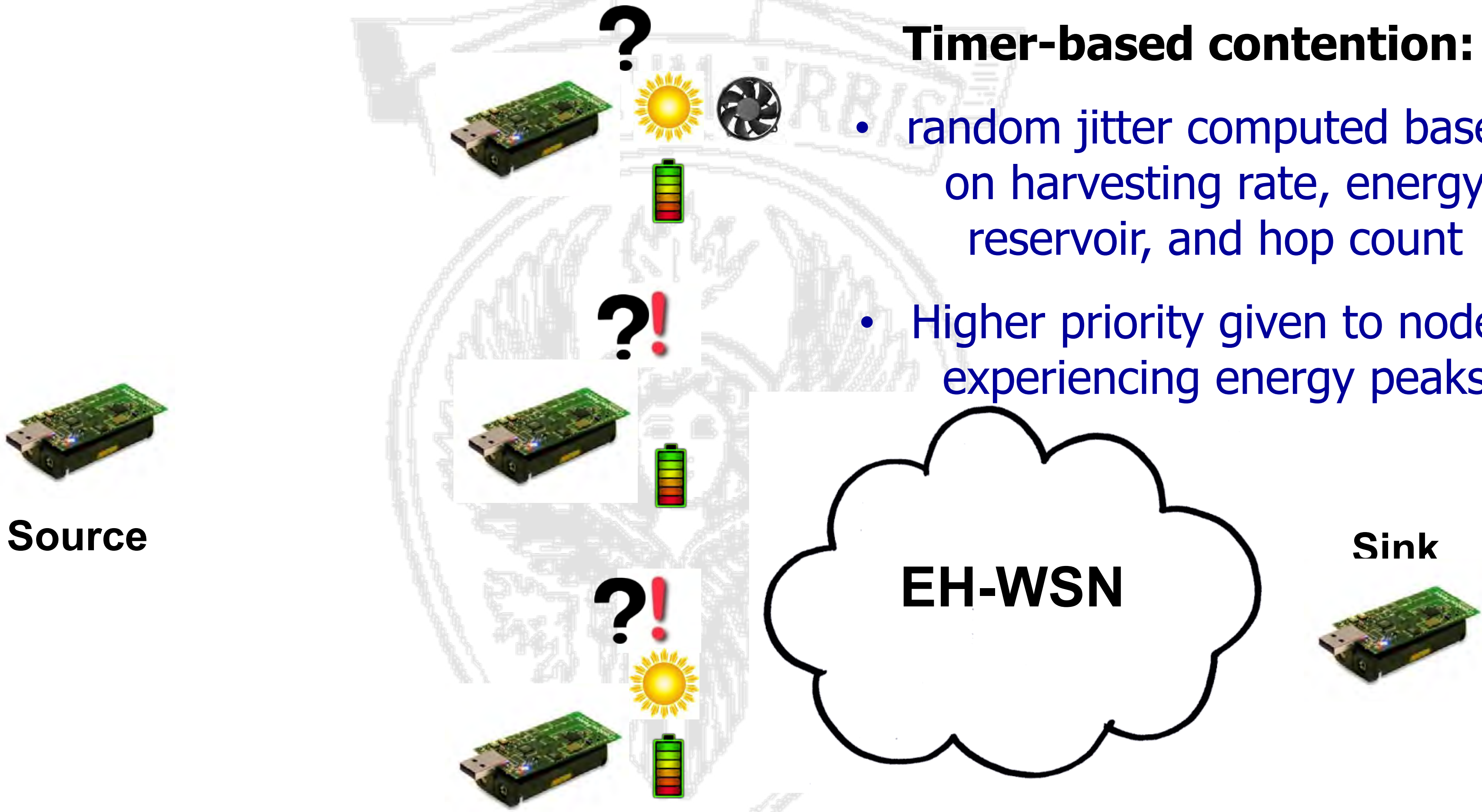

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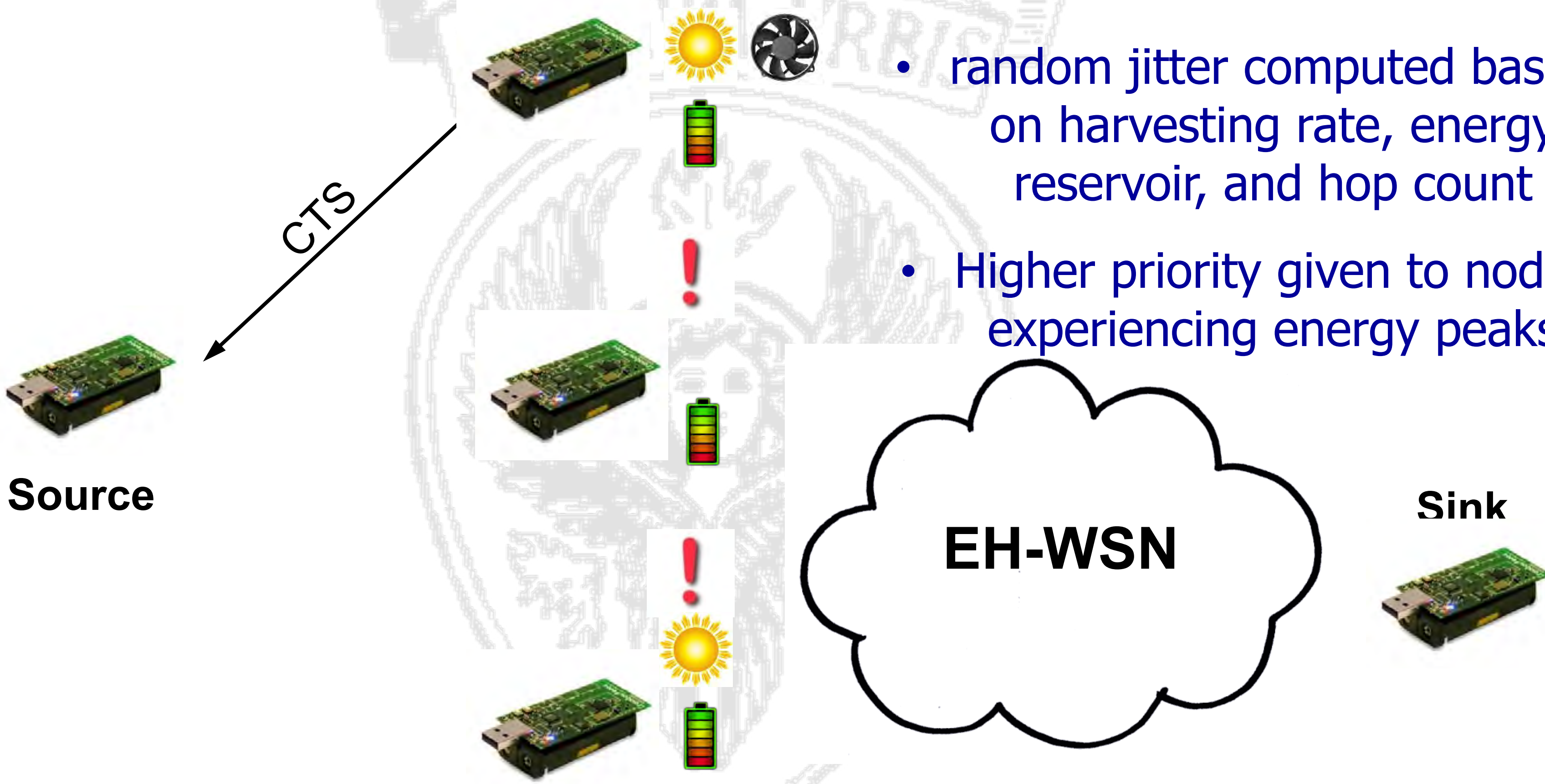
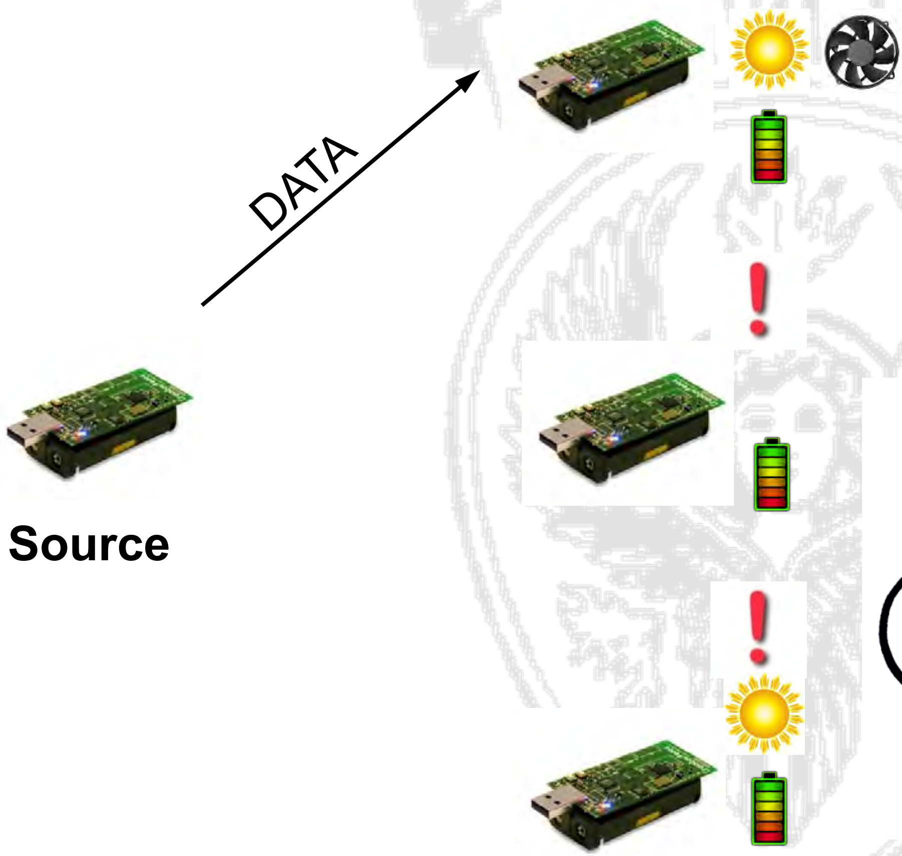


Harvesting-aware routing



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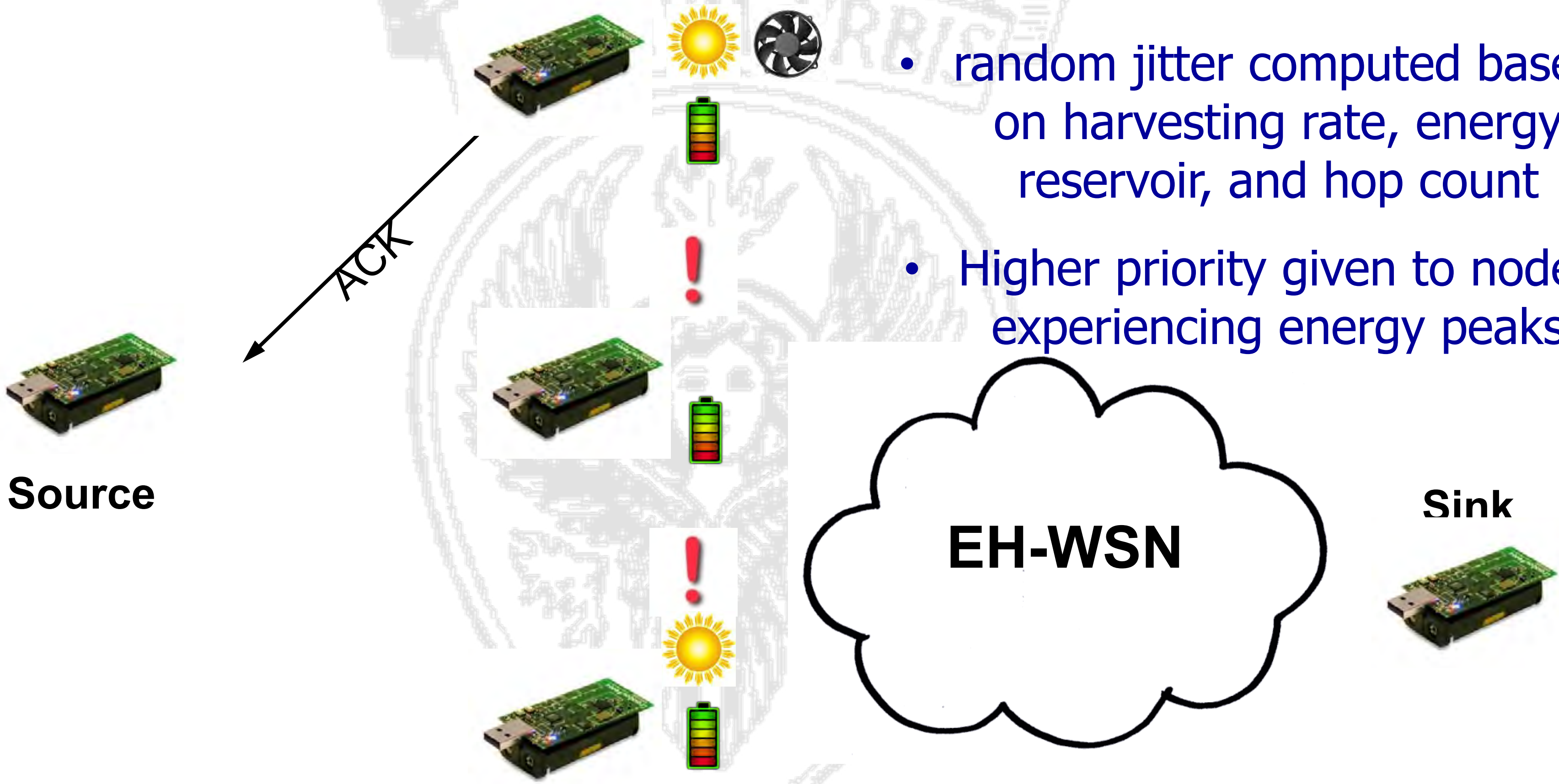
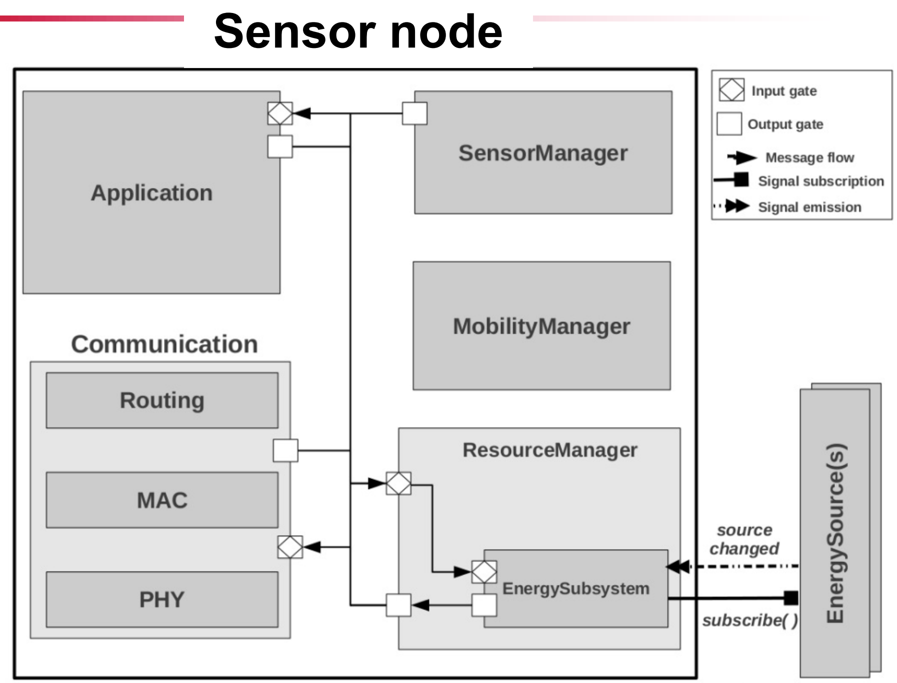


GreenCastalia: Motivation

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



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

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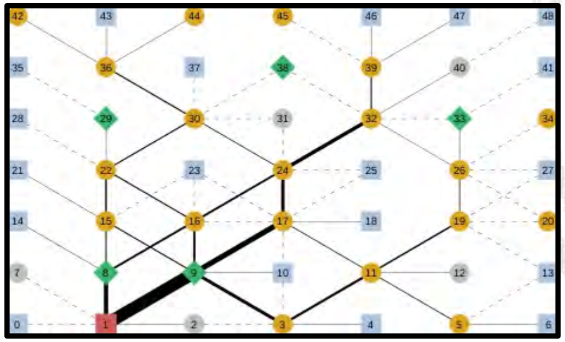
Harvesting-aware routing: Results

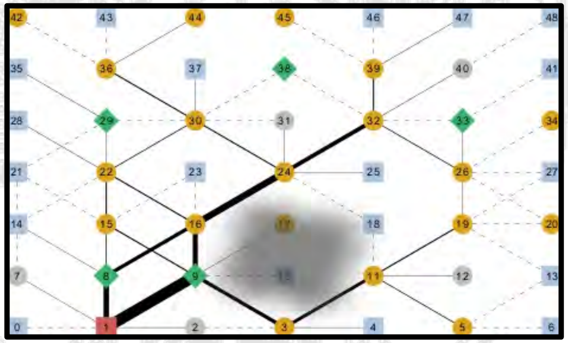
Simulation settings

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

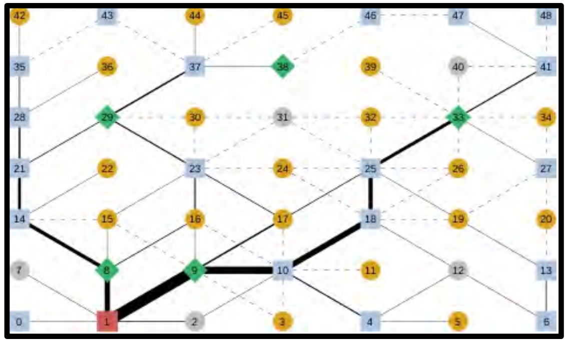
11am



5pm with shadow zone



8pm

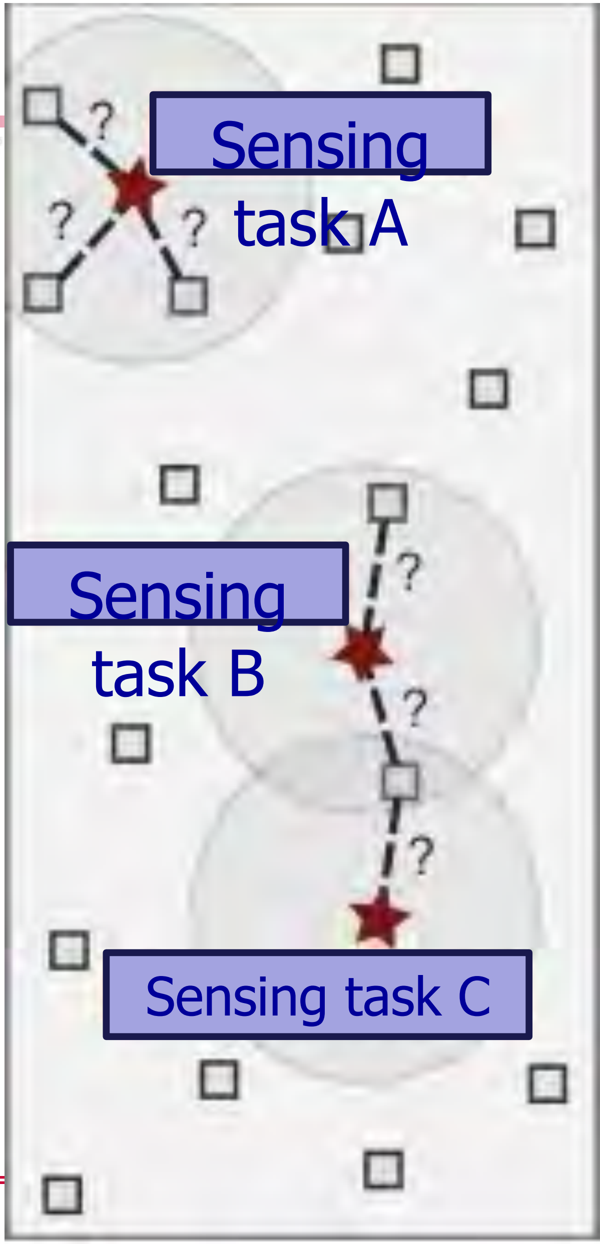


Self-adaptive behaviour: nodes experiencing energy peaks are selected with higher priority as next hop relays

Task allocation

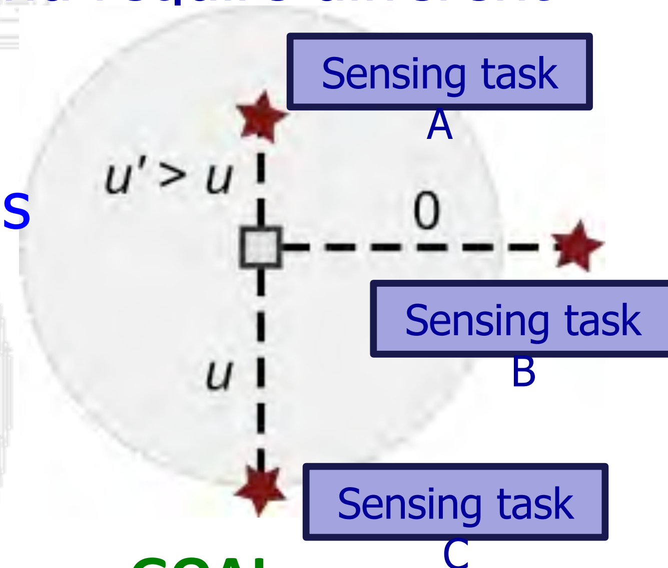
- Sensing tasks (missions) arrive in the network dynamically over time at different locations
- Multiple missions active at the same time, competing for the sensing resources of the network

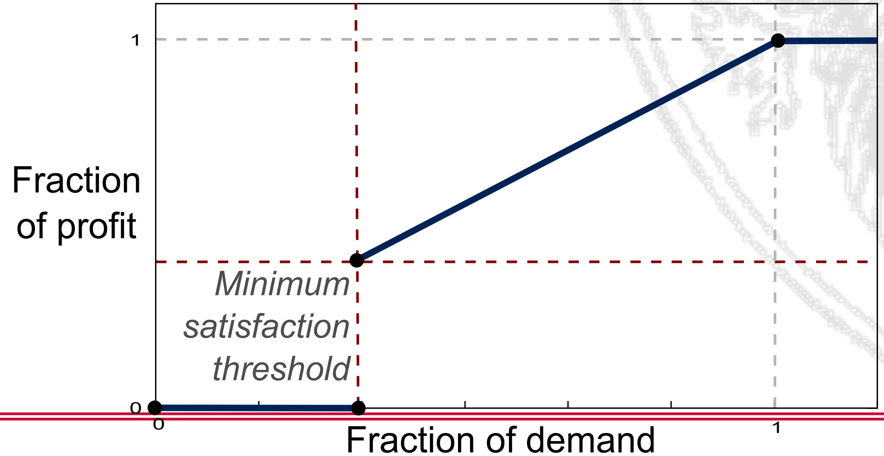
Decide which sensor(s) should be assigned to each mission



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

Task-Allocation EN-MASSE-In summary

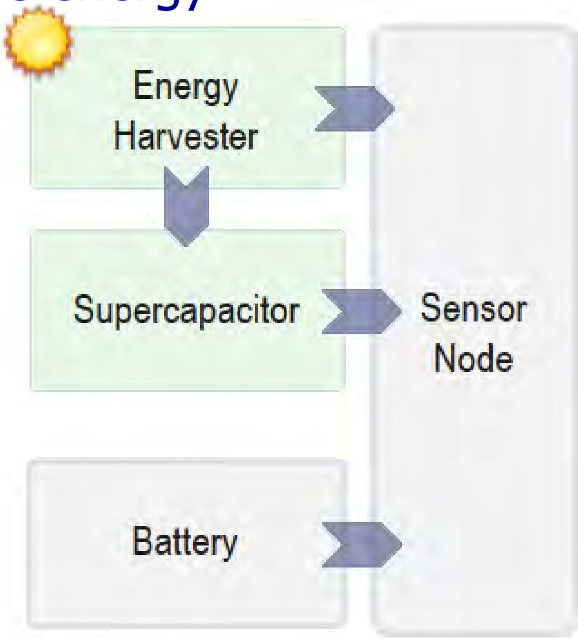
A **decentralized** harvesting-aware heuristic

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



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

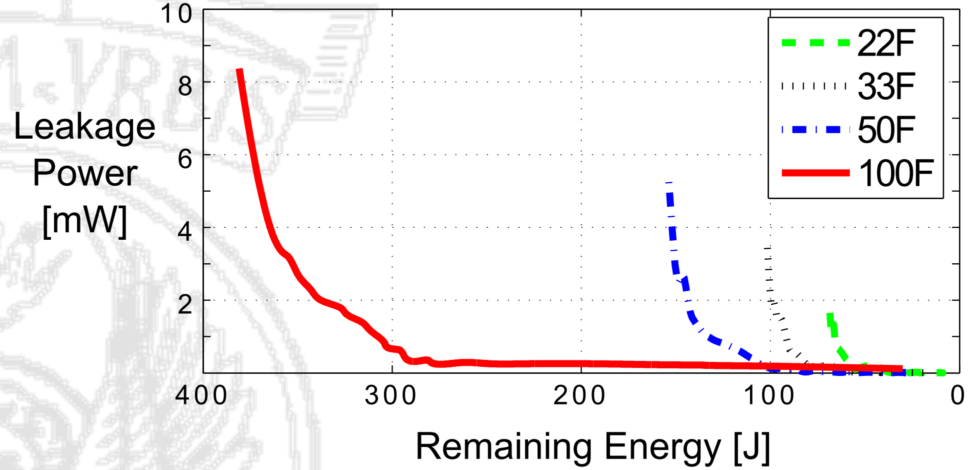
$$p^* = \frac{e_{ij}}{d_j} \times \frac{p_j}{P} \times w$$

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

Modeling real harvesting systems

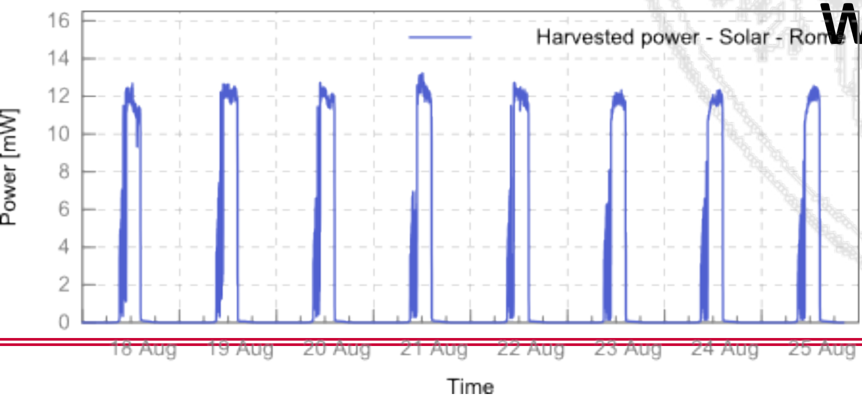
Non-ideal supercapacitors

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

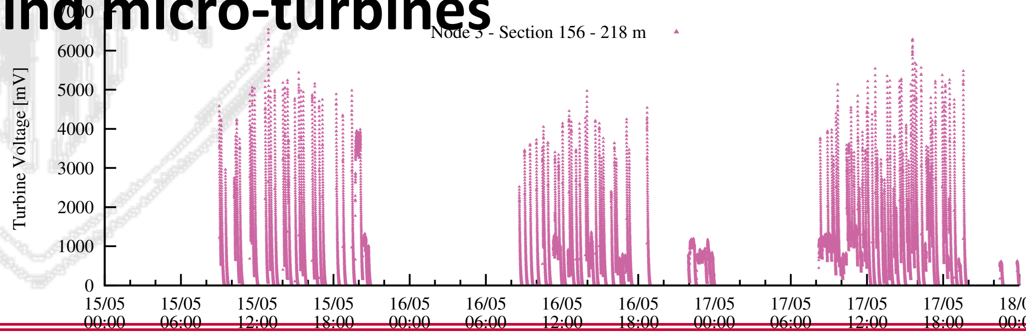


Real-life energy traces

Photovoltaic cells



Wind micro-turbines



Perf. evaluation

Table II. Simulation scenarios: default settings.

Parameter	Value
Nodes in the network	500
Simulation field	400 × 400 m
Communication range	40 m
Sensing range	30 m
Average mission profit	10
Average mission demand	2
Average mission duration	1 hour
Satisfaction threshold	50% of the mission demand

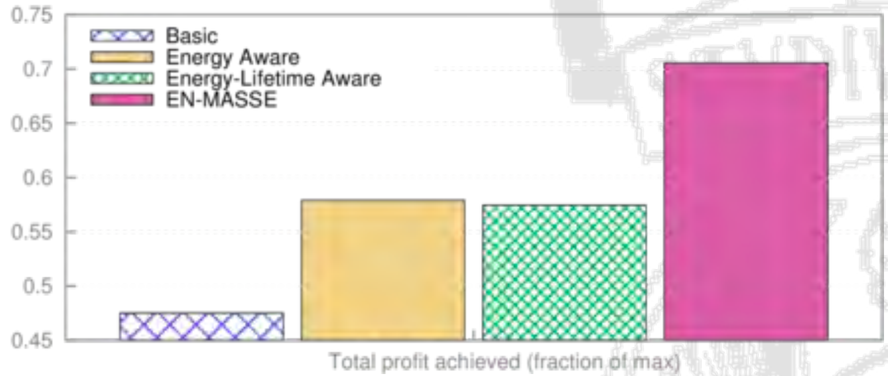
Perf. evaluation

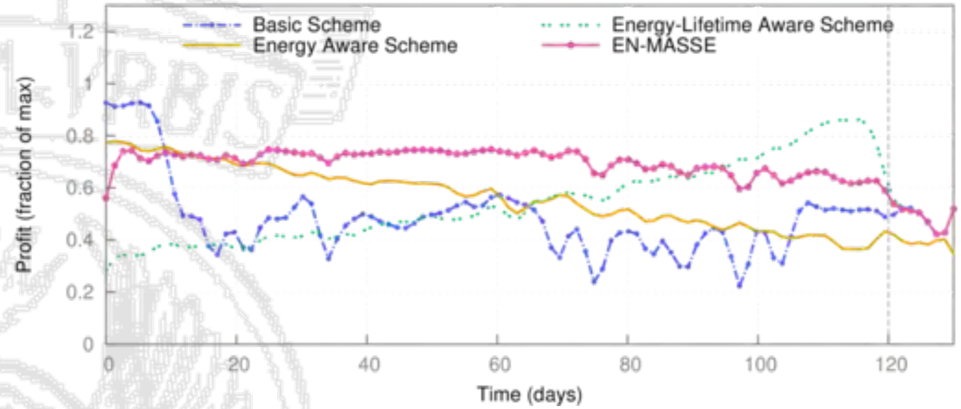
Basic scheme: Nodes always bid for missions within their range

Energy aware scheme: Bids based on profit provided vs. expected profit, weight only considers battery level

Energy lifetime aware scheme: as above but weight set based on active sensing time a node could support given its available batery energy/expected occupancy time till network lifetime

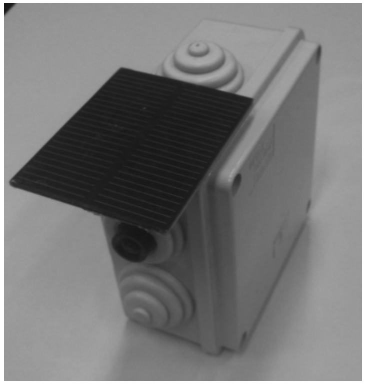
Performance evaluation

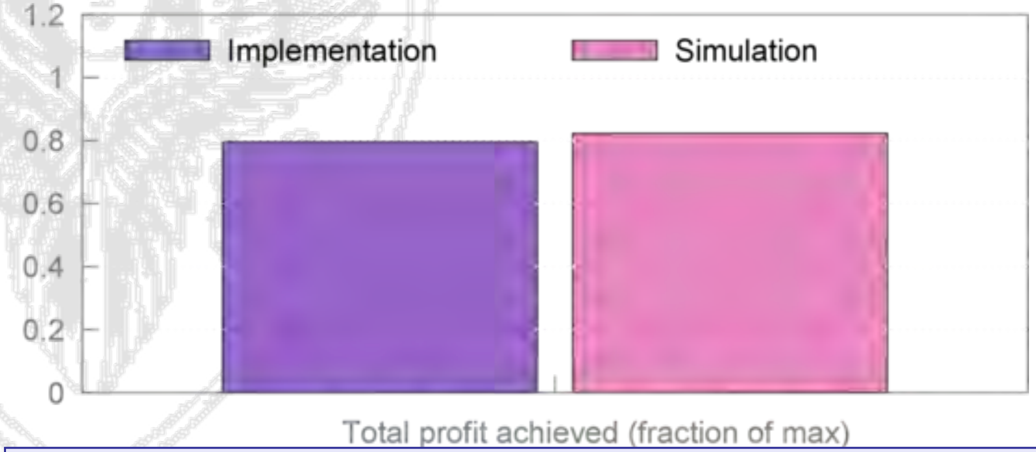




Profit: **up to 60% higher** **than SoA**

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





In-field testbed validation

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

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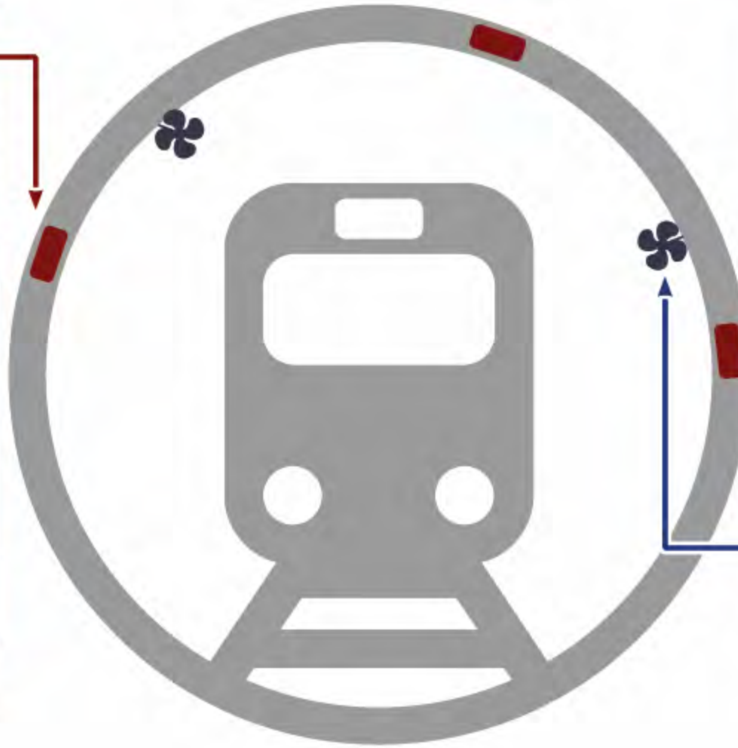
Rome underground testbed

Vibrating Wire Strain Gauges

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

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



Micro wind turbines

Energy harvesting from wind generated by trains

Why air-flow energy harvesting?

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

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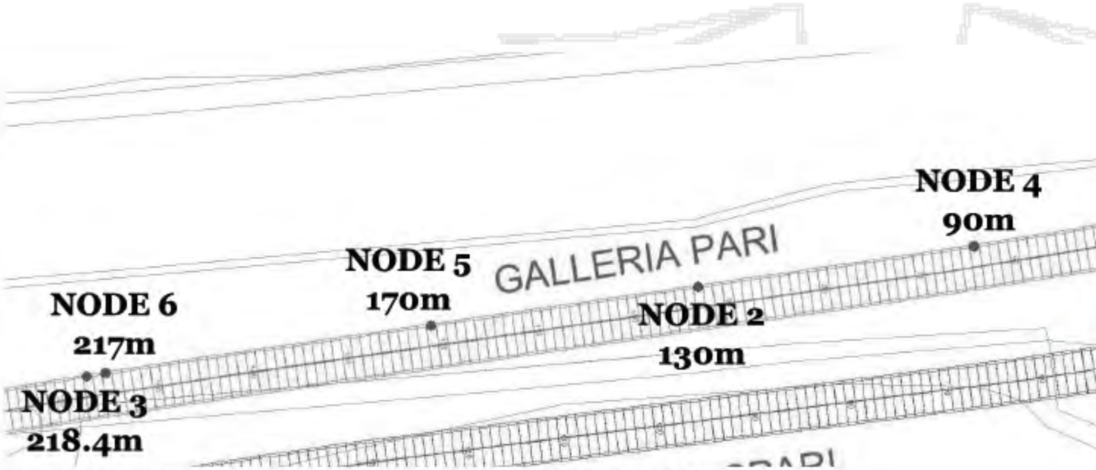
In-field air-flow data collection



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

220 meter of instrumented tunnel

6 energy-harvesting nodes

33 days of data collection

Feasibility study

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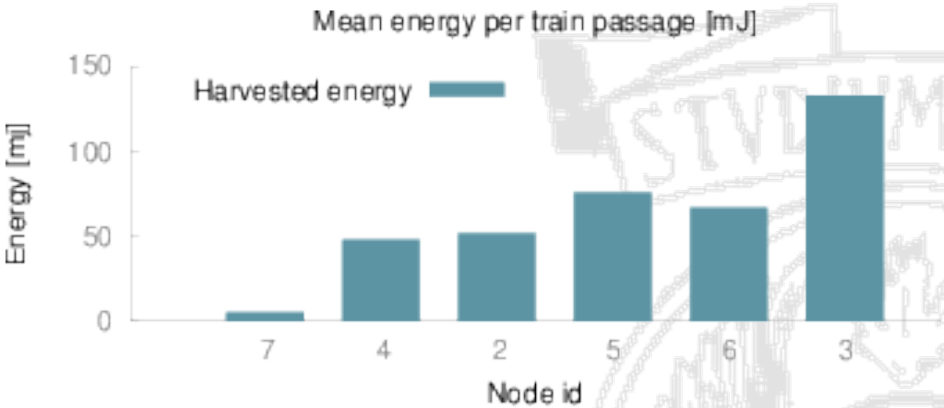
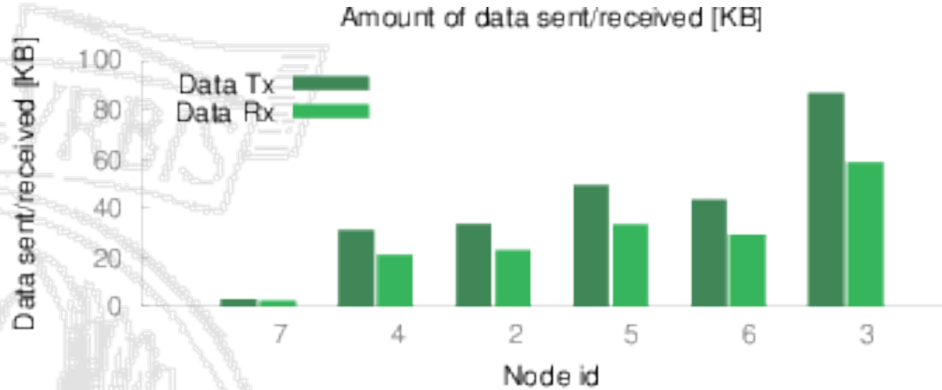
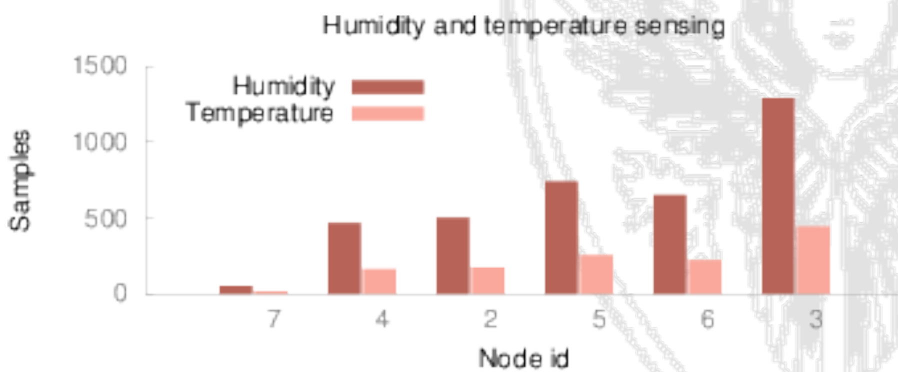


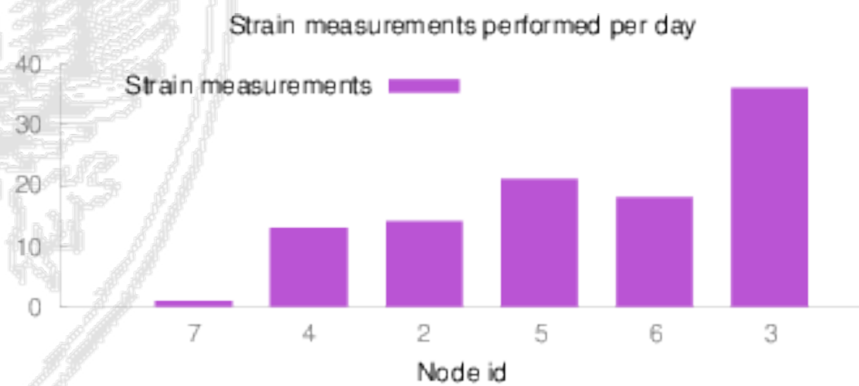
Up to 133 mJ harvested per train passage



Transmit/receive tens of KB



Collect hundreds of humidity and temperature samples



Up to 36 strain measurements per day

Protocols for wake-up radio enabled Internet of Things, a.a. 2015/2016

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Chiara Petrioli[†]

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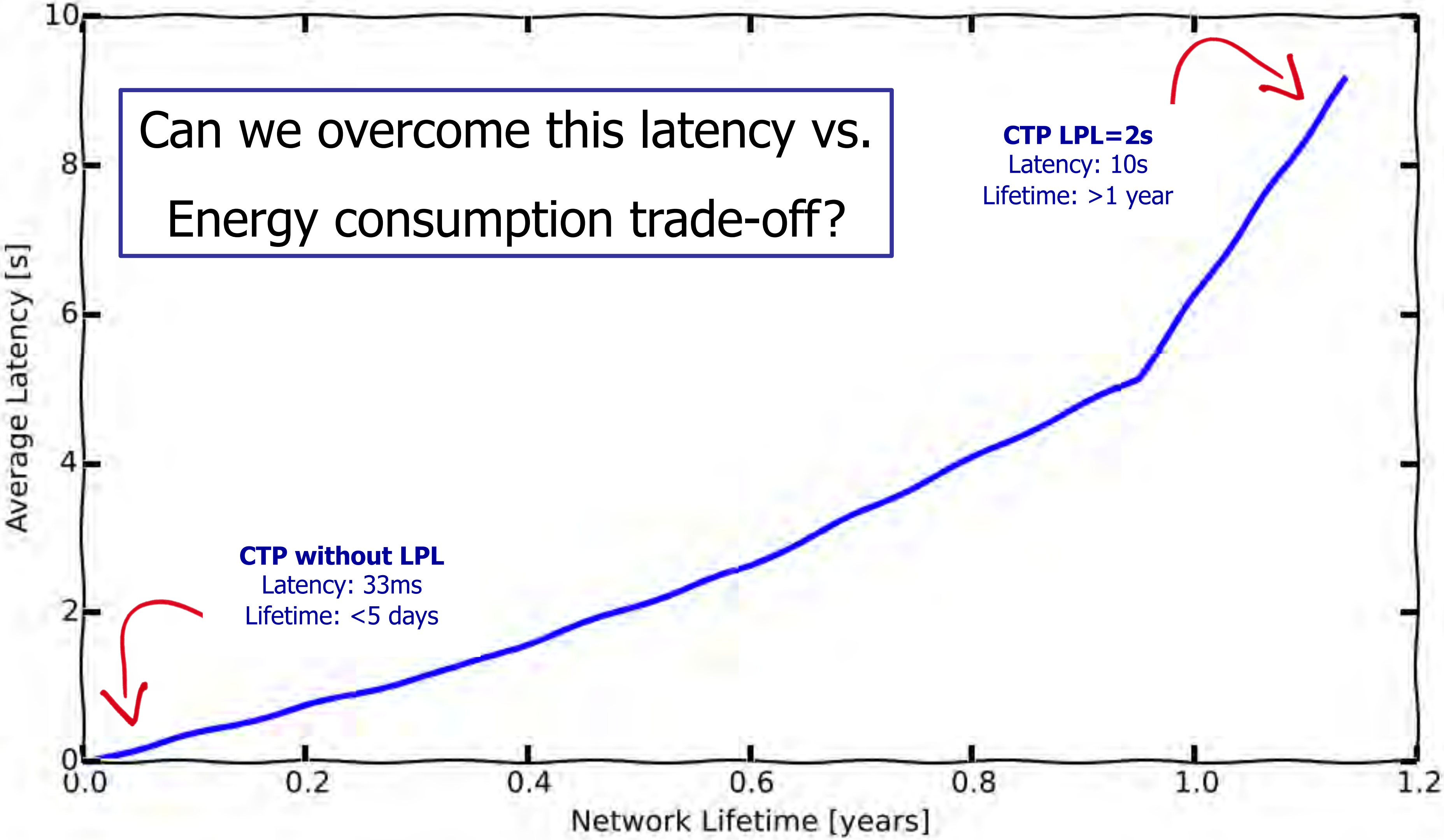
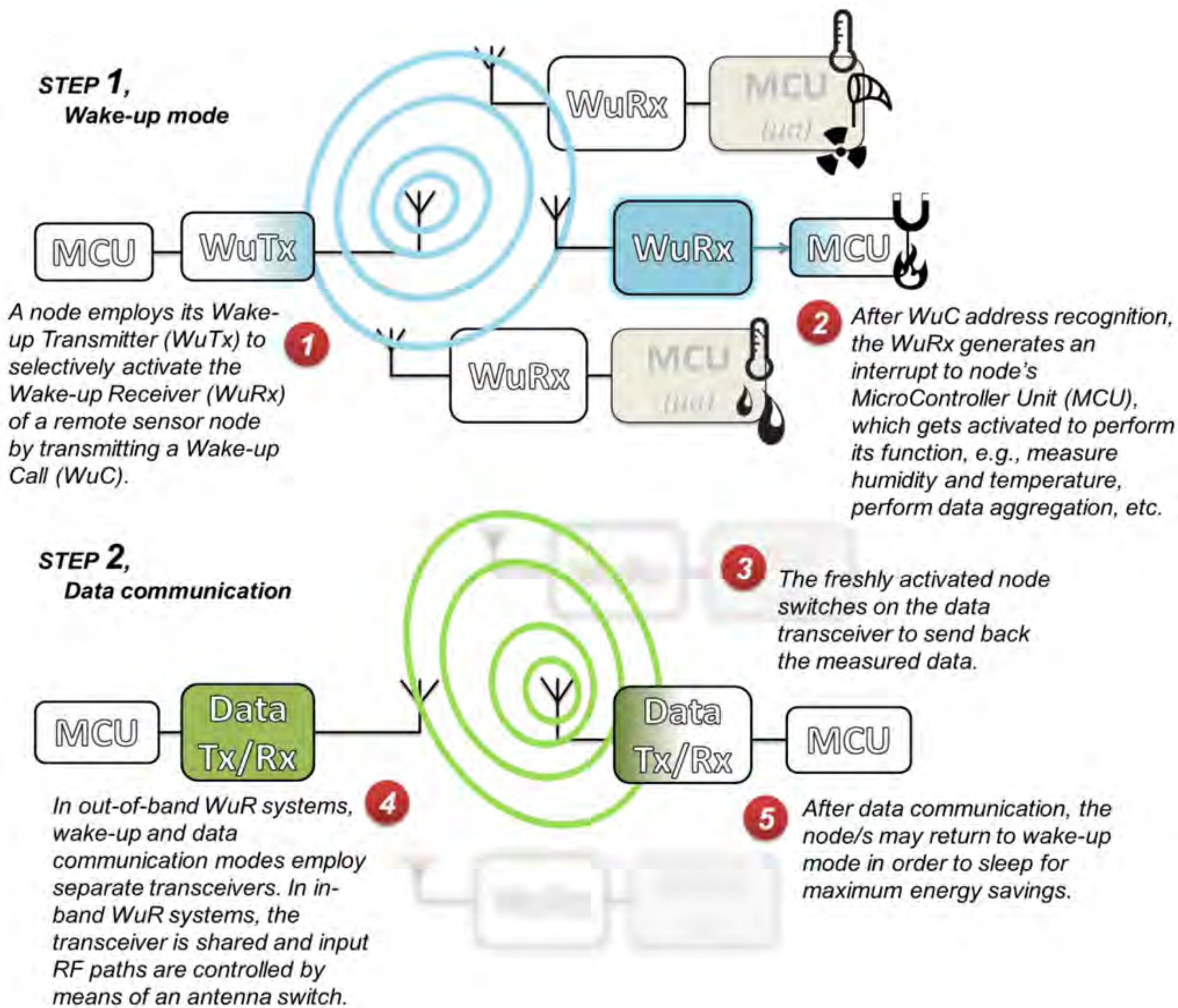
Latency vs. Energy Trade-off



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

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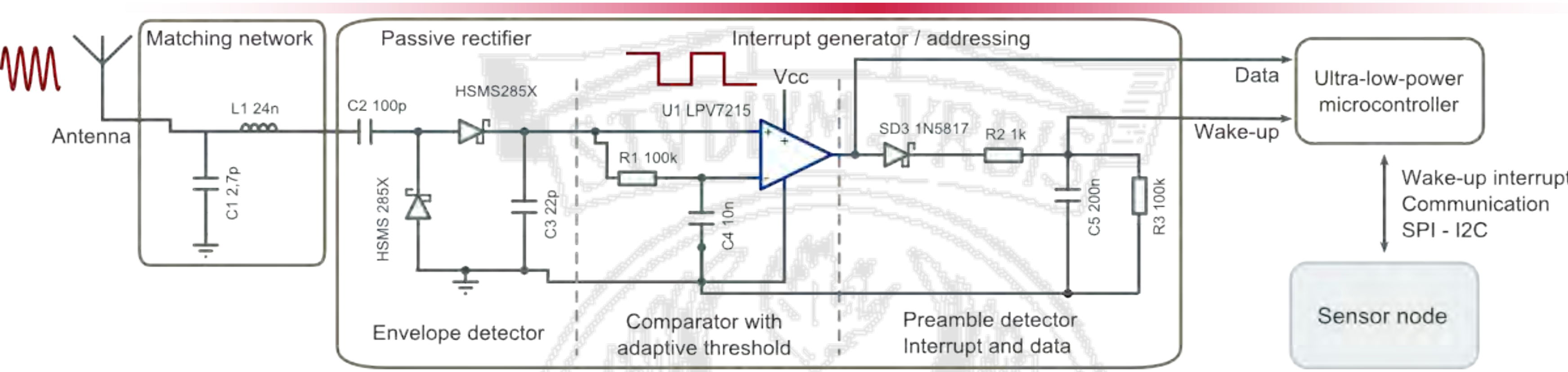
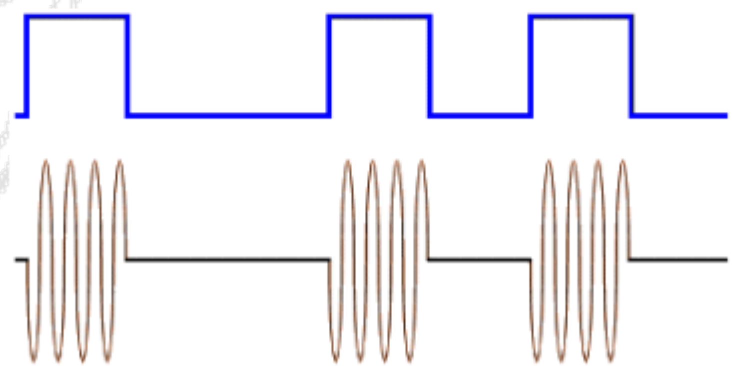
Our wake-up radio architecture

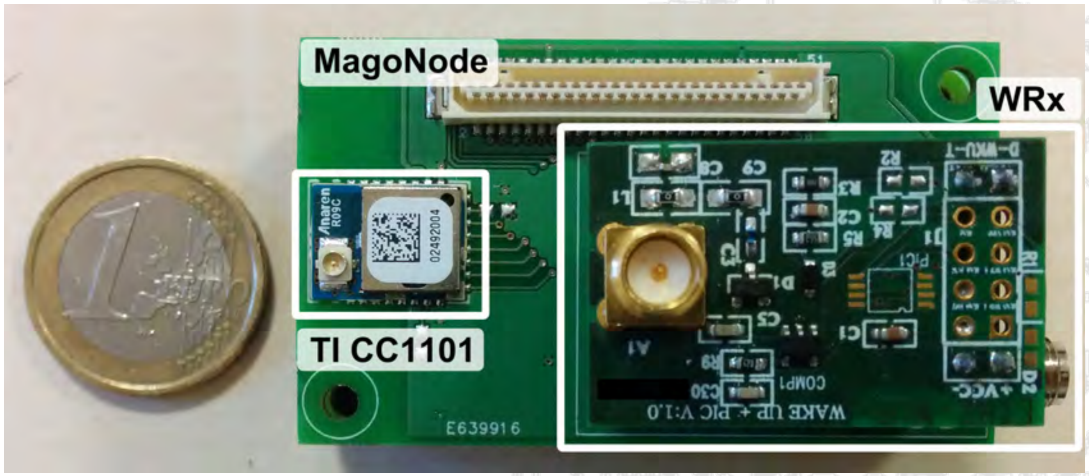


Collaboration with L. Benini and M. Magno, ETHZ

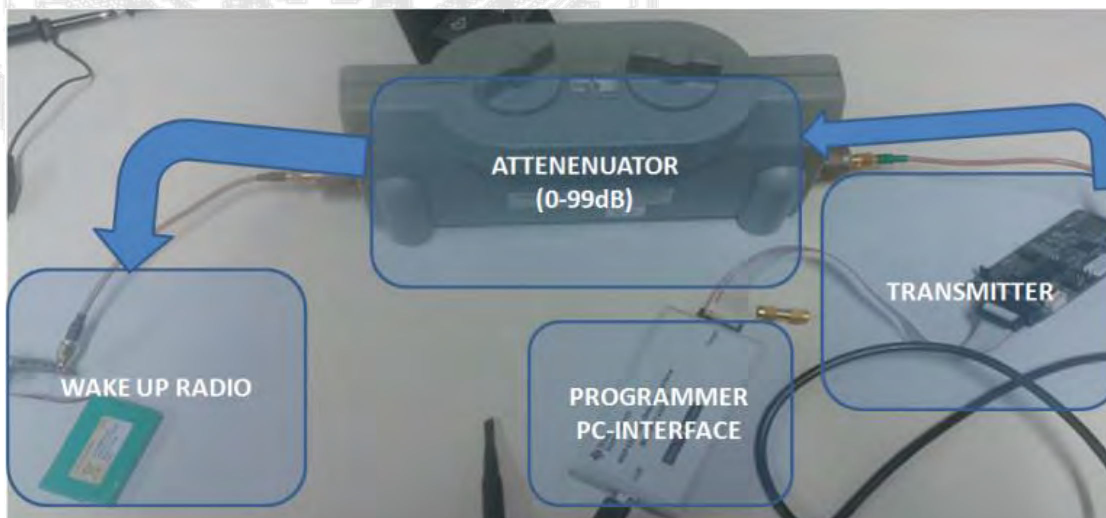
- OOK modulation
- Very low power consumption (< 1.3uW)
- High sensitivity (up to -49dBm)
- Fast reactivity (wake-up time of 130us)
- **Selective addressing**



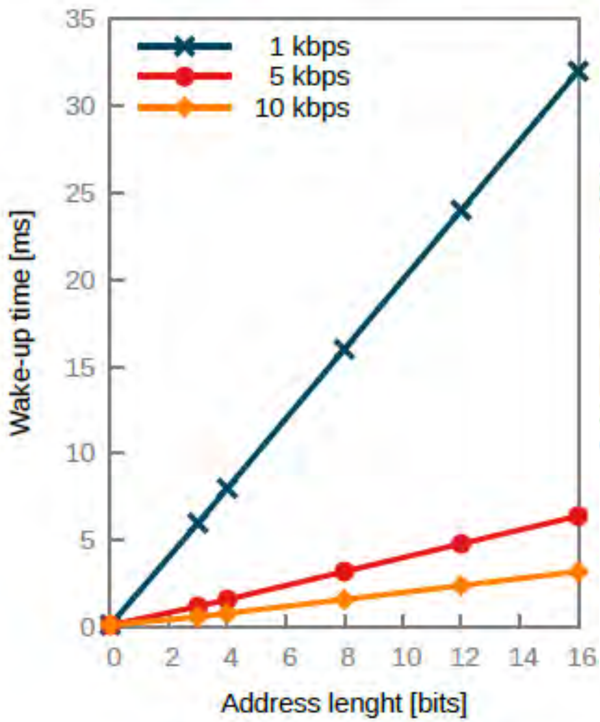
WRx prototyping and testing



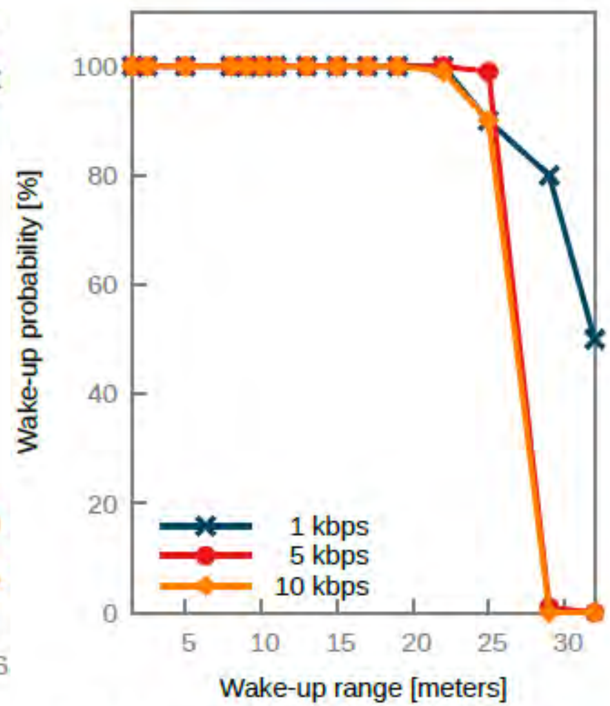
- TI CC1101 used to transmit WRx requests
- on-board PIC microcontroller to perform addressing while keeping the MagoNode in deep-sleep



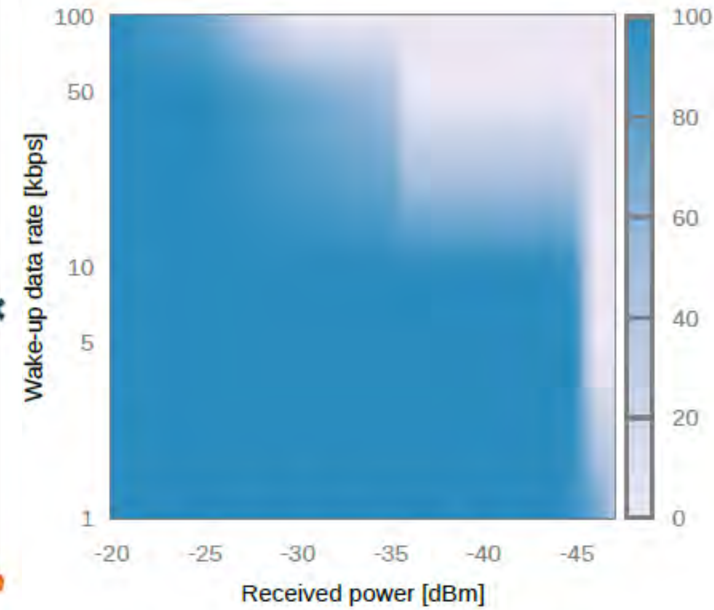
Experimental performance



(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 communication stack

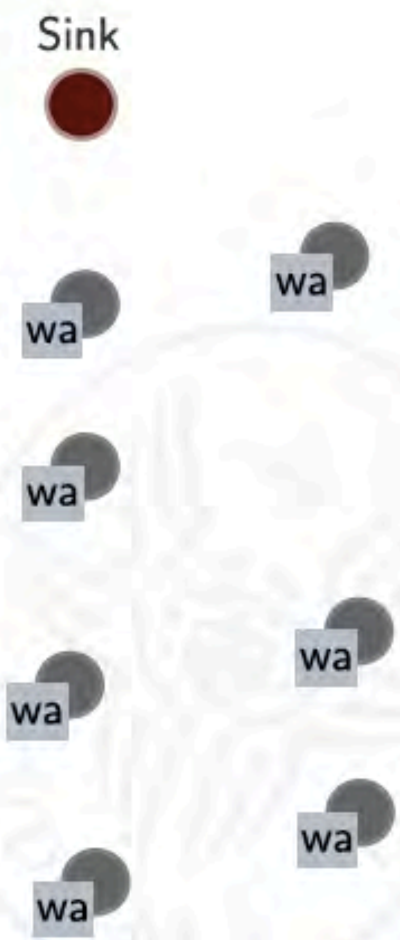
- Exploits proposed WuR to addresses latency vs. energy consumption tradeoff
- Both interest dissemination and convergecasting primitives
- **Key idea**: use wake-up addresses to wake up a node or a group of nodes based on certain properties

Interest dissemination

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

FLOOD-WUP

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



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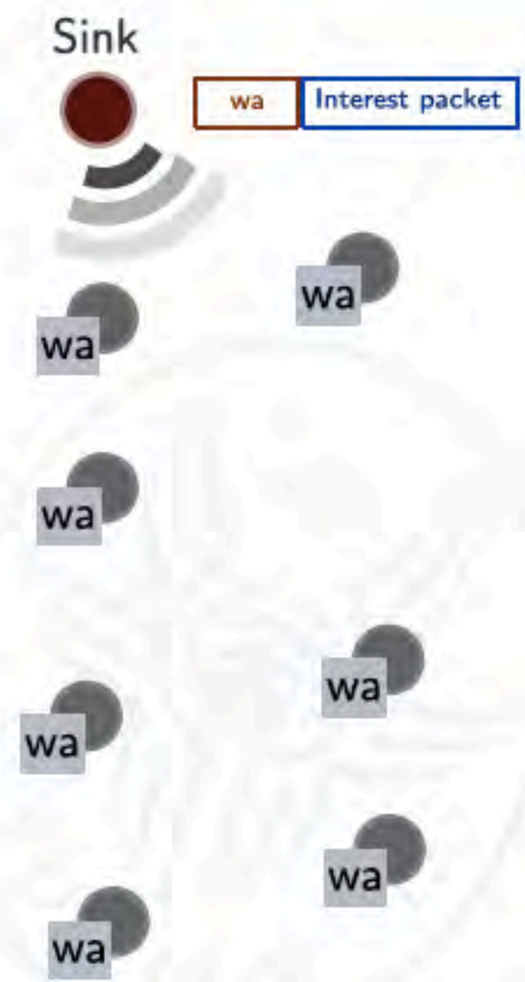

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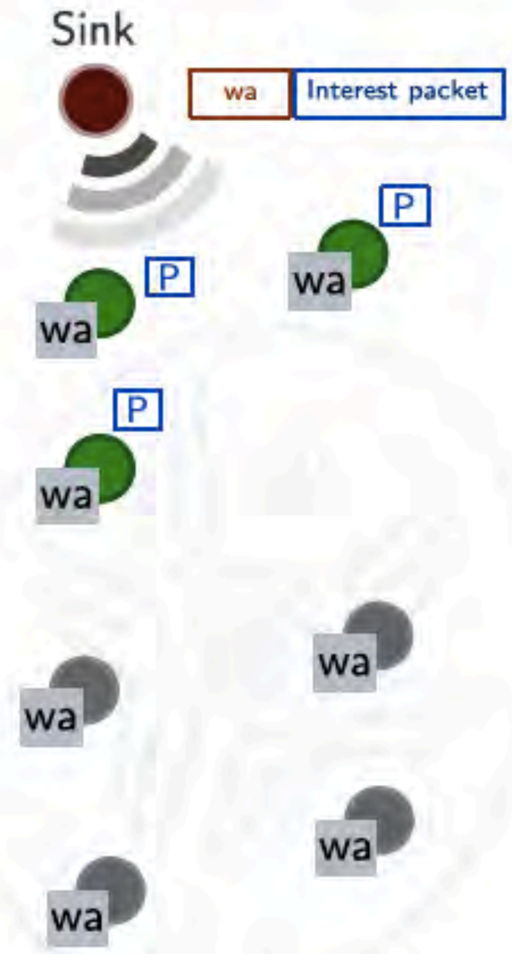

Flood-WUP

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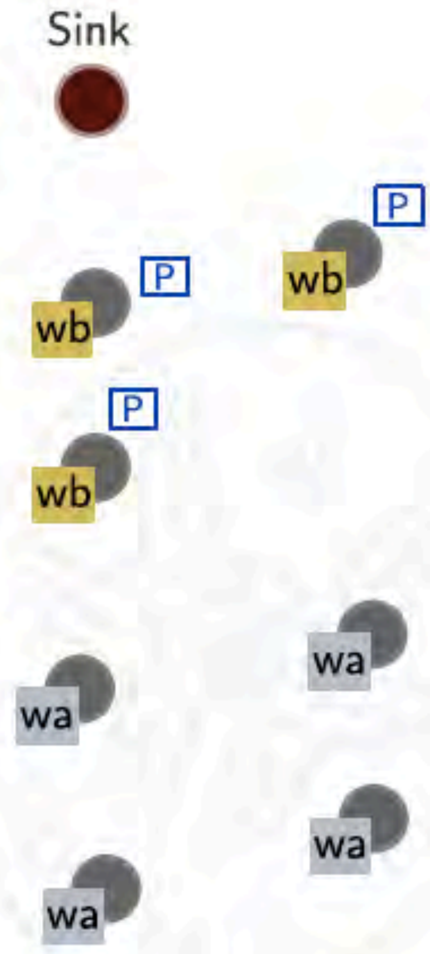
- Then change broadcast wake-up address to w_b



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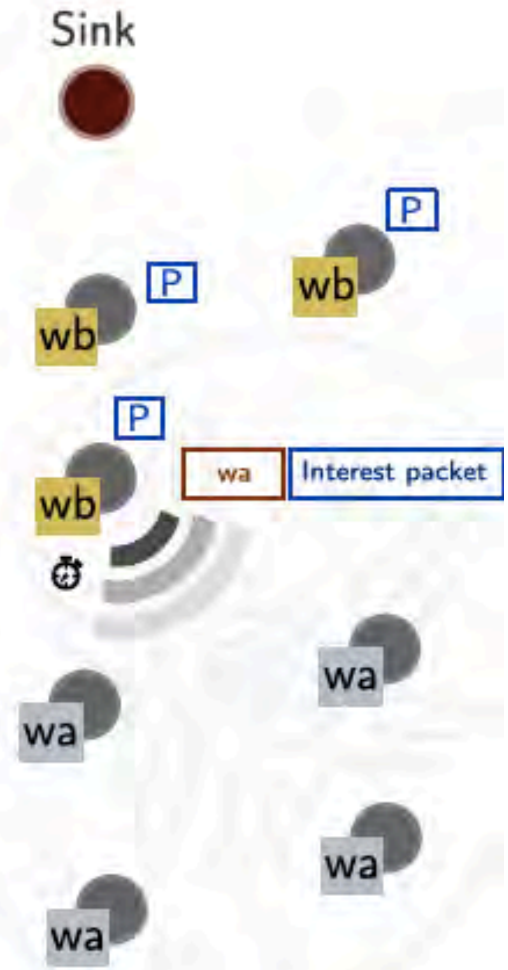
- Then change broadcast wake-up address to w_b
- After a random time, nodes re-broadcast packet preceding it with w_a



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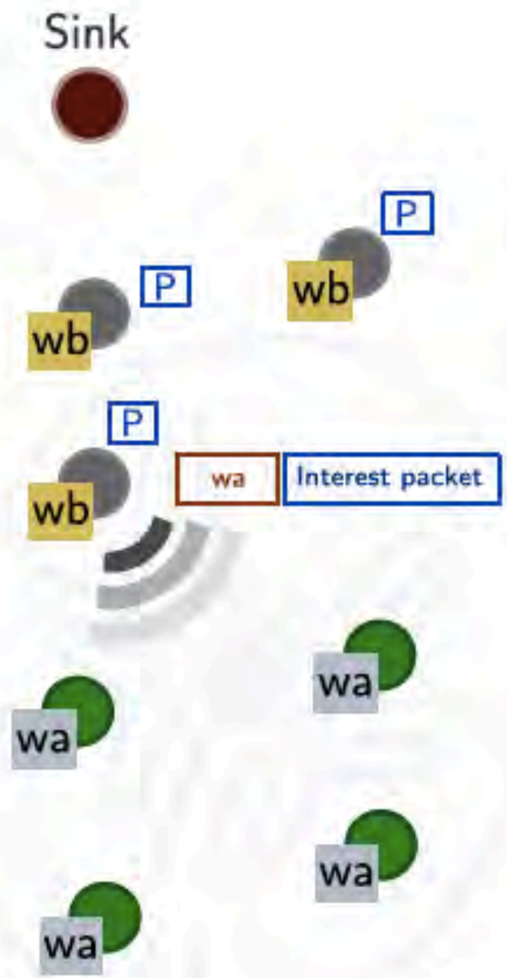
- Nodes with address w_a wakes up, sets main radio to RX, receive packet
- Then change broadcast wake-up address to w_b
- After a random time, nodes re-broadcast packet preceding it with w_a
- **No duplicates, only nodes with address w_a wake up**



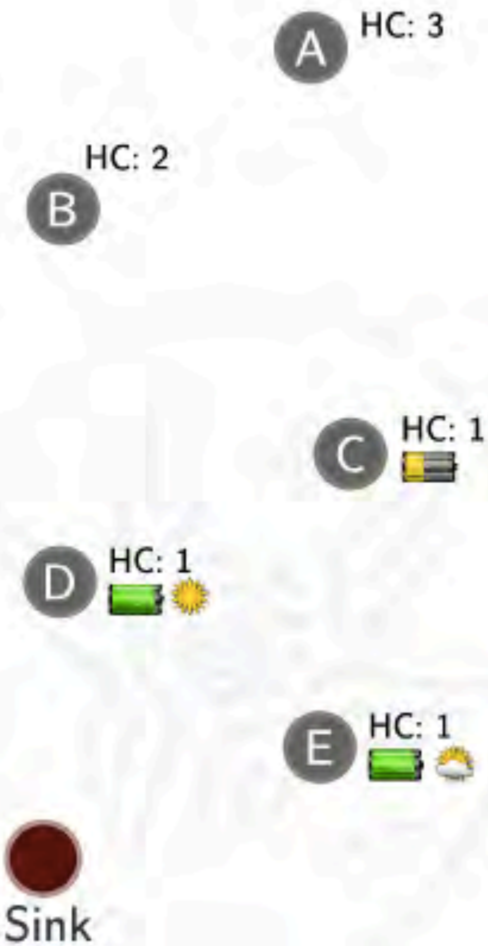
Converge Casting: GREEN-WUP

- 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 ≤ T_{high}
  0 battery level ≤ T_{low}



GREEN-WUP

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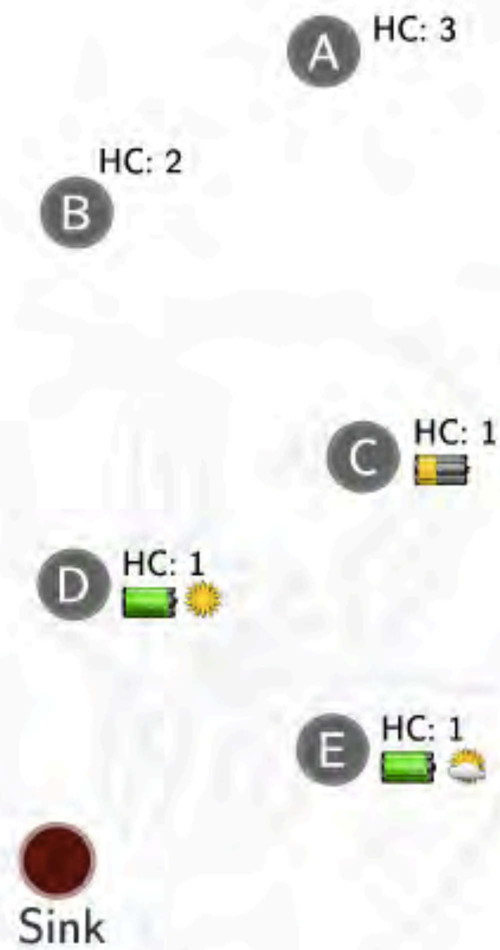
- Node B has a packet to transmit



GREEN-WUP

- Example: energy classes

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  2 battery level > T_{high}
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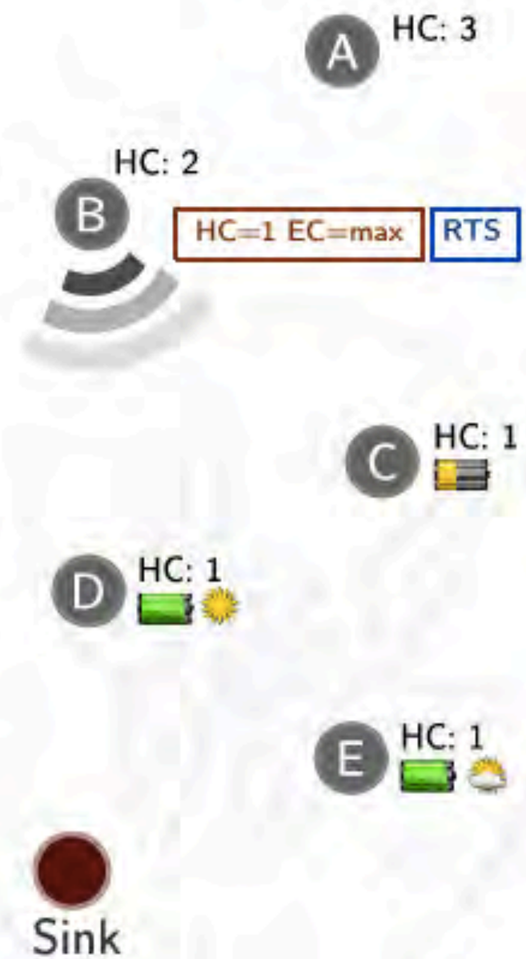
  0 battery level ≤ T_{low}

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



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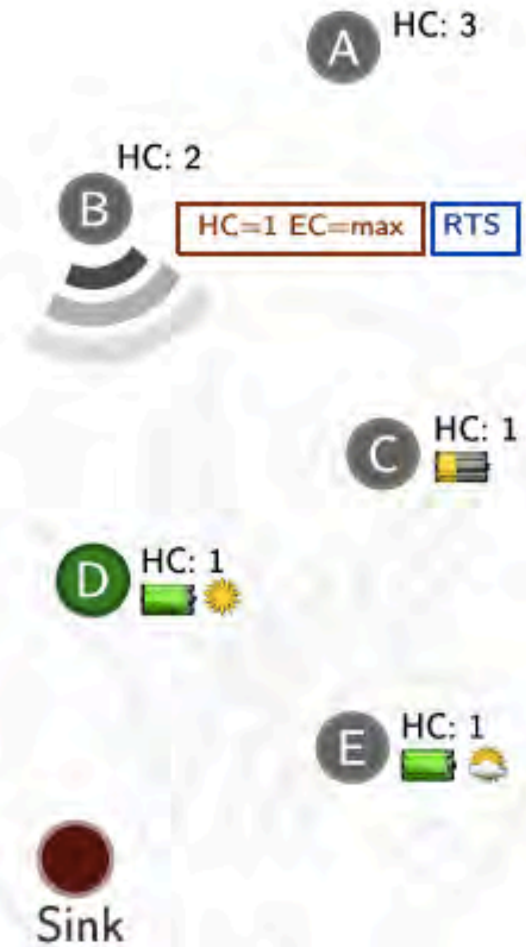
- Node B has a packet to transmit
- Sends RTS only to nodes with hopcount = 1 and energy = max. Then it goes to sleep
- Only node D wakes up. Other nodes continues to sleep



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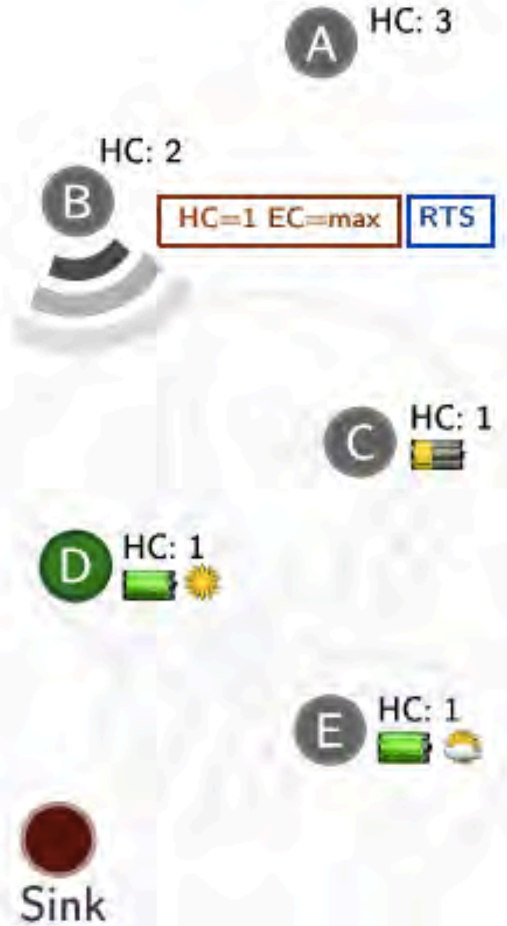
- Only node D wakes up. Other nodes continues to sleep
- Iterate on energy class if no relay found



GREEN-WUP

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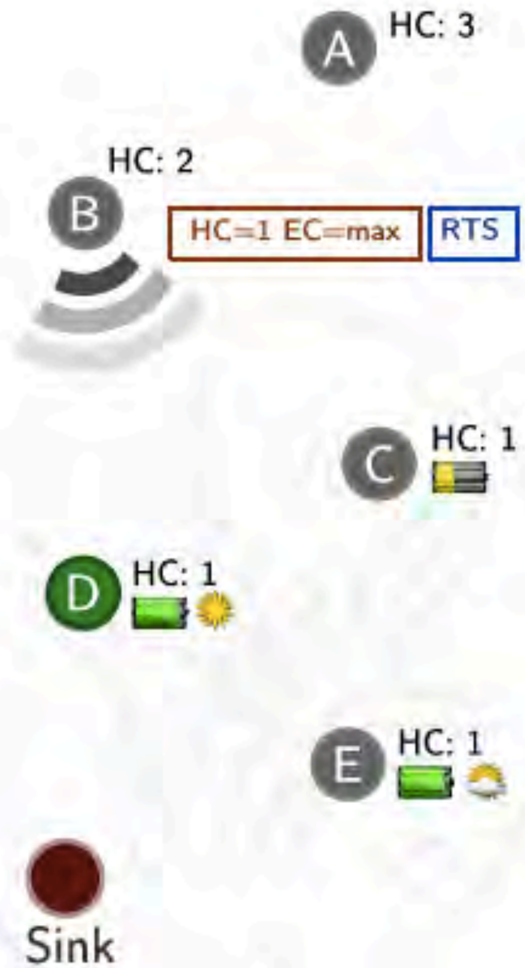
- Only node D wakes up. Other nodes continues to sleep
- Iterate on energy class if no relay found
- CTS, DATA, ACK..



Sim. scenario

Different concept of wake up radio

- Active, higher energy consumption

+ Semantic WUP radio addresses

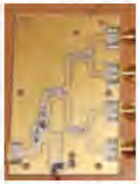
+ Only one transceiver (TX)

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)



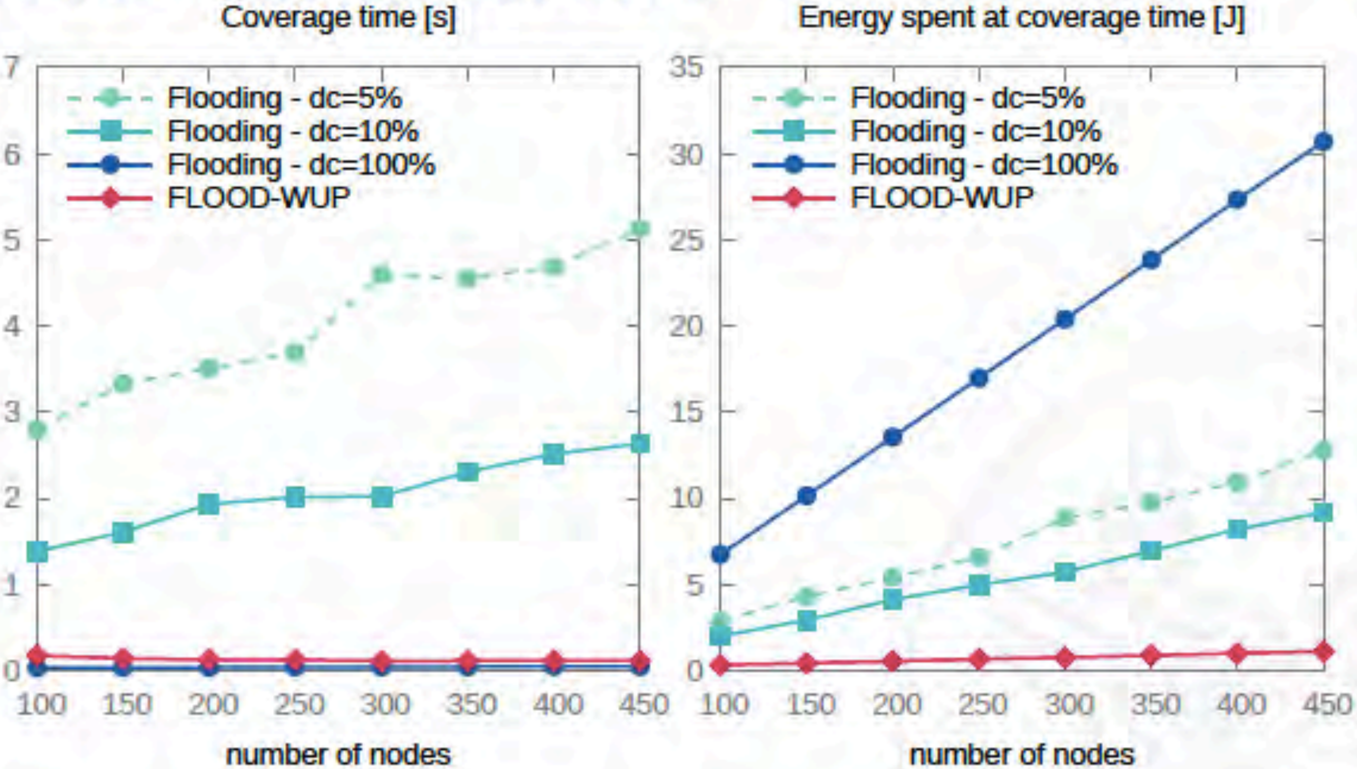
Green Castalia simulations

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

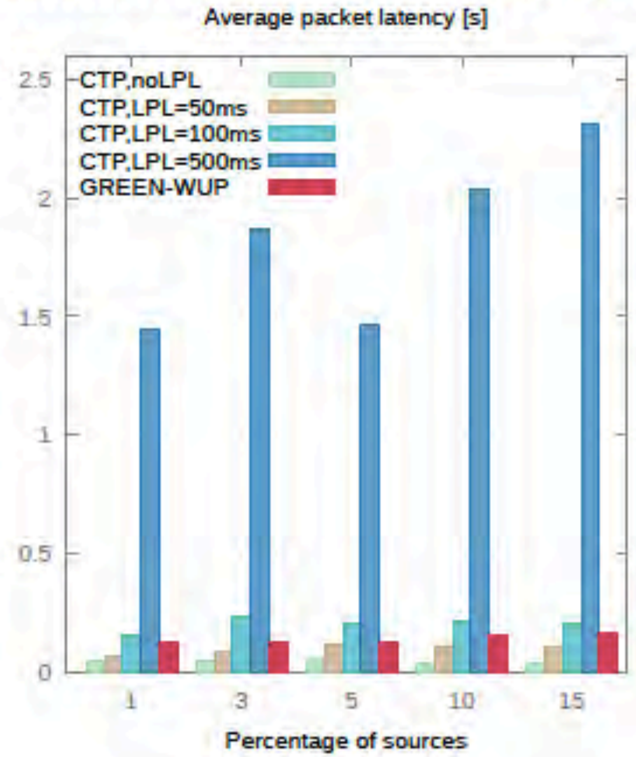


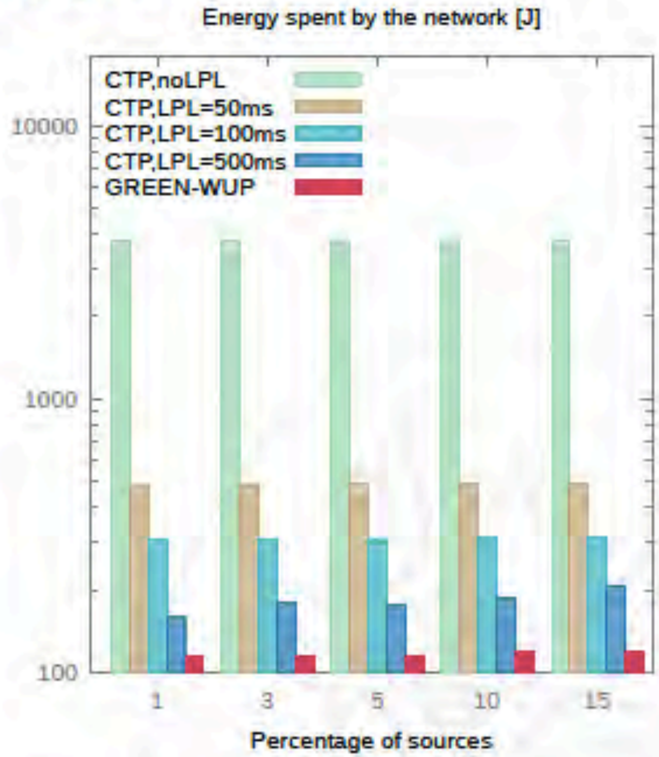
Coverage time similar to Flooding with 100% DC

Energy consumption reduced of up to ≈ 96%

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

GREEN-WUP, network of 100 nodes



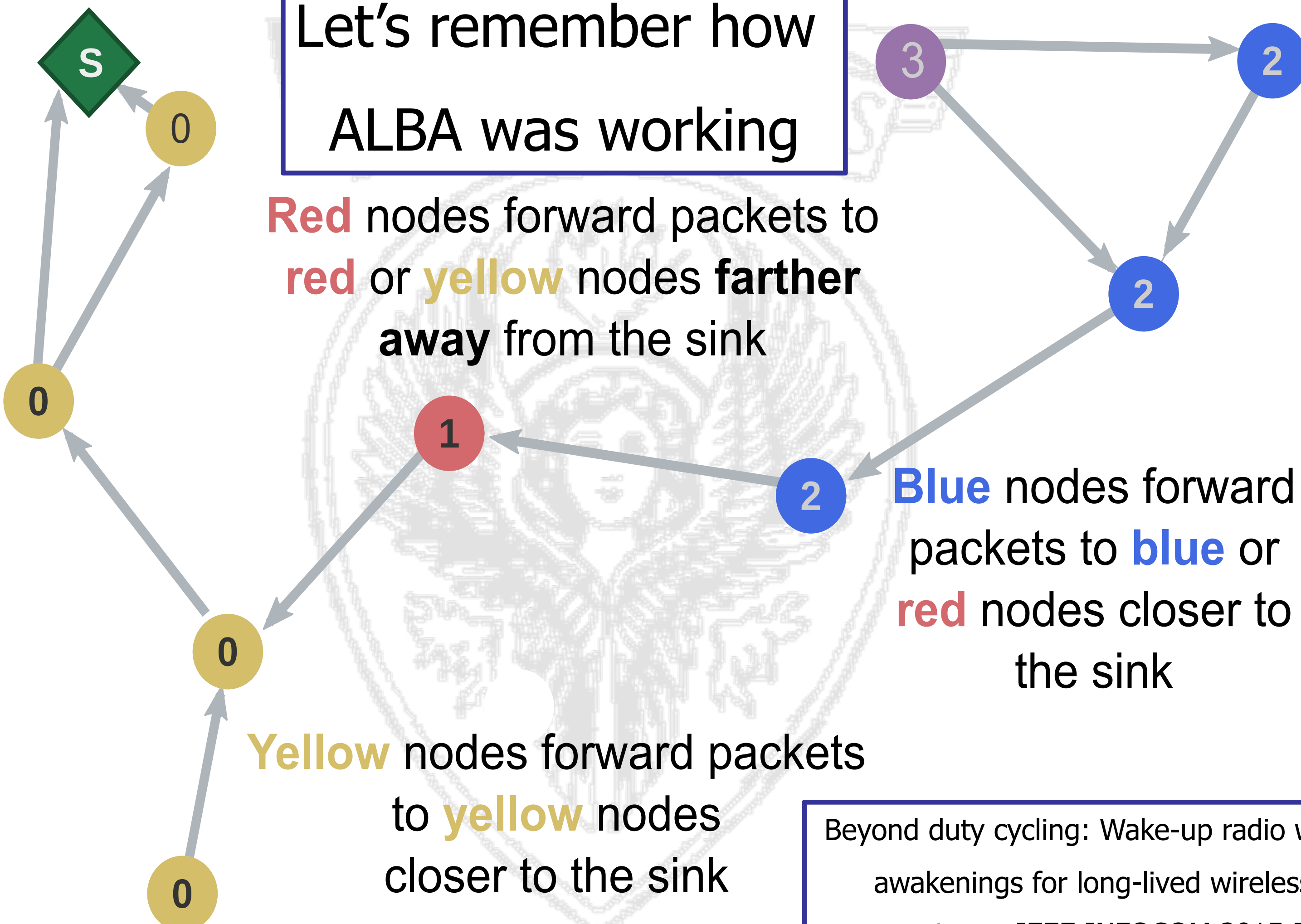


Average latency 100 ms higher than CTP without LPL

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

Let's Redesign: ALBA-WUR

- ALBA-R: The best relay is selected among the nodes that are awake
- ALBA-WUR: We wake up good potential relays when we need them
- Semantic addressing: WUR addresses reflect fundamental parameters—color, available queue space and QPI

Semantic Addressing

- When a node has a packet to send, it wakes up only good potential relay

Color = Red	Burst size = 2	Target QPI = 1

- Each node maintains a pool of WUR addresses, each corresponding to a request it can serve
- GPI is taken into account when answering to WUR requests

Semantic Addressing: Example

- Receiver:
  - Color: Red; queue occupancy: 1 (of 3);moving average of recent transmissions: 2, and maximum number of packets that can be sent in a burst: 2

Color = Red	Burst Size = 1	QPI = 1
Color = Red	Burst Size = 2	QPI = 2
Color = Blue	Burst Size = 1	QPI = 1
Color = Blue	Burst Size = 2	QPI = 2

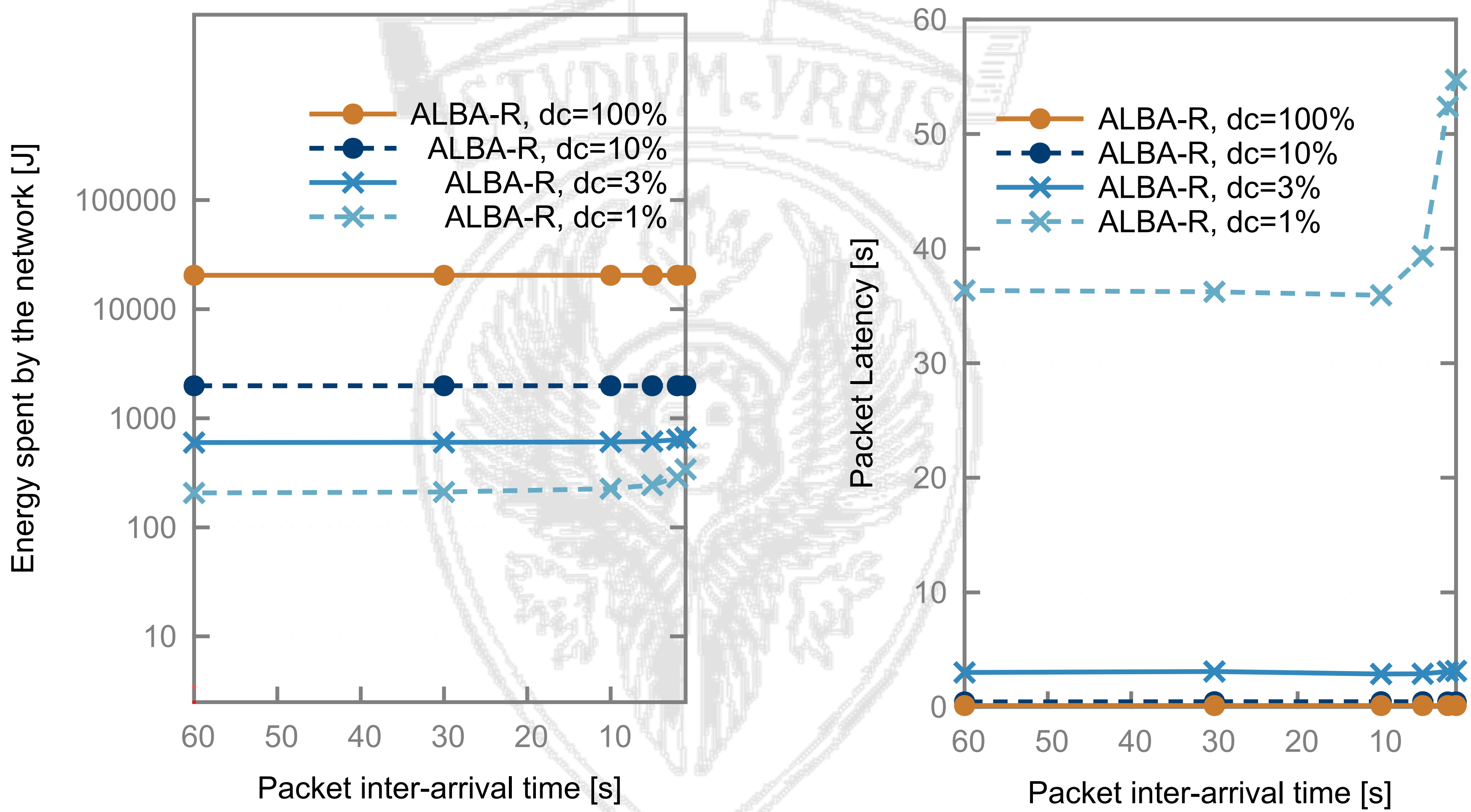
- Sender:

Color = Blue	Burst size = 1	Target QPI = 1

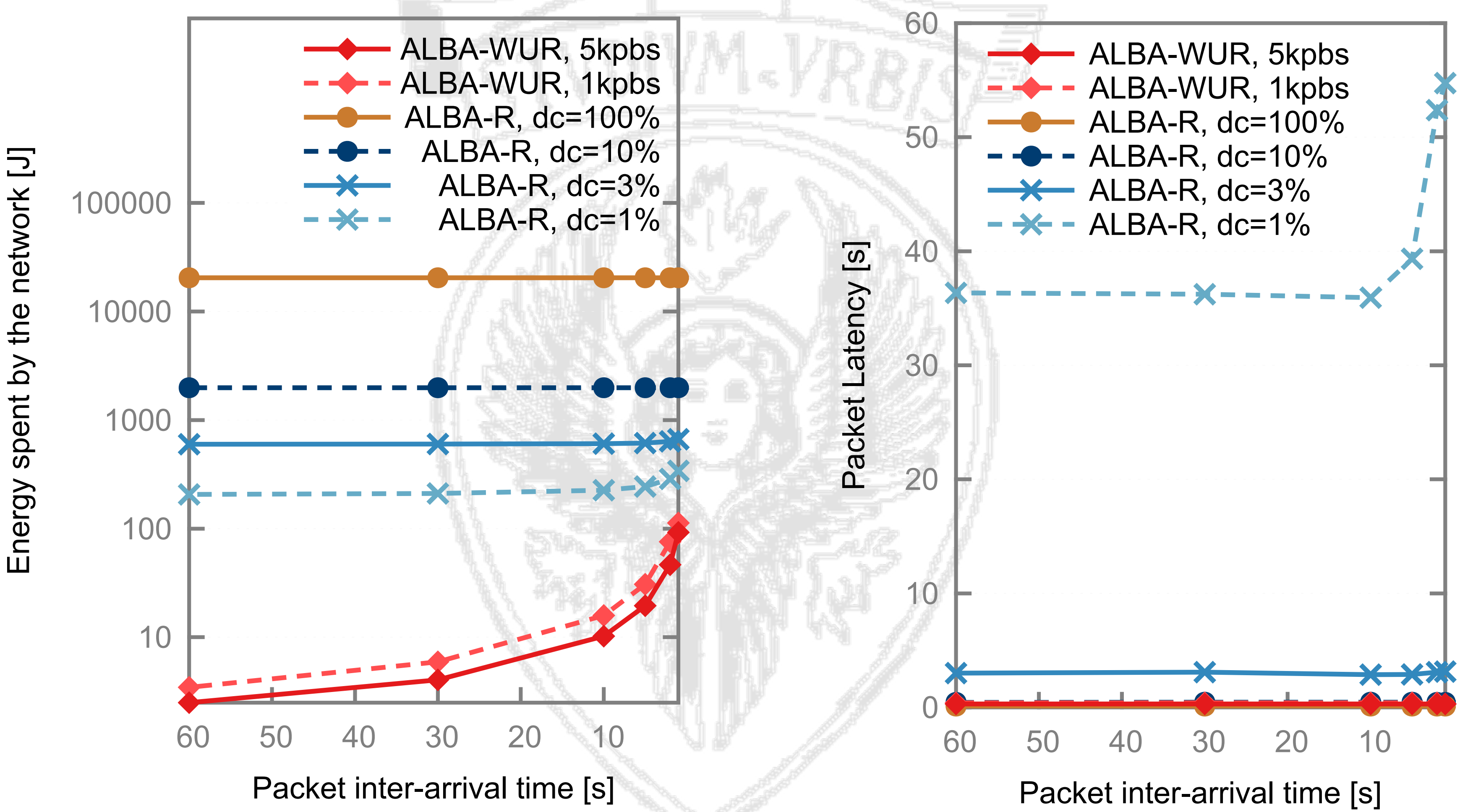
Simulation Results: Set Up

- Simulation framework: Green Castalia
- Developed extensions: MagoNode, WUR, module, WTx module
- Realistic energy and WUR models based on actual measurements and experiments
- Comparison with ALBA-R with duty cycles:100%, 10%, 3%, 1%
- 120 nodes distributed randomly and uniformly over a 200x200m field
- Data traffic: λ packets per second (Poisson process)

ALBA-WUR vs. ALBA-R: Energy Consumption and Latency



ALBA-WUR vs. ALBA-R: Energy Consumption and Latency



ALBA-WUR vs. ALBA-R: Energy Consumption and Latency

- Energy consumption reduced by up to three orders of magnitude
- Latency comparable to that of ALBA-R with 100% duty cycle

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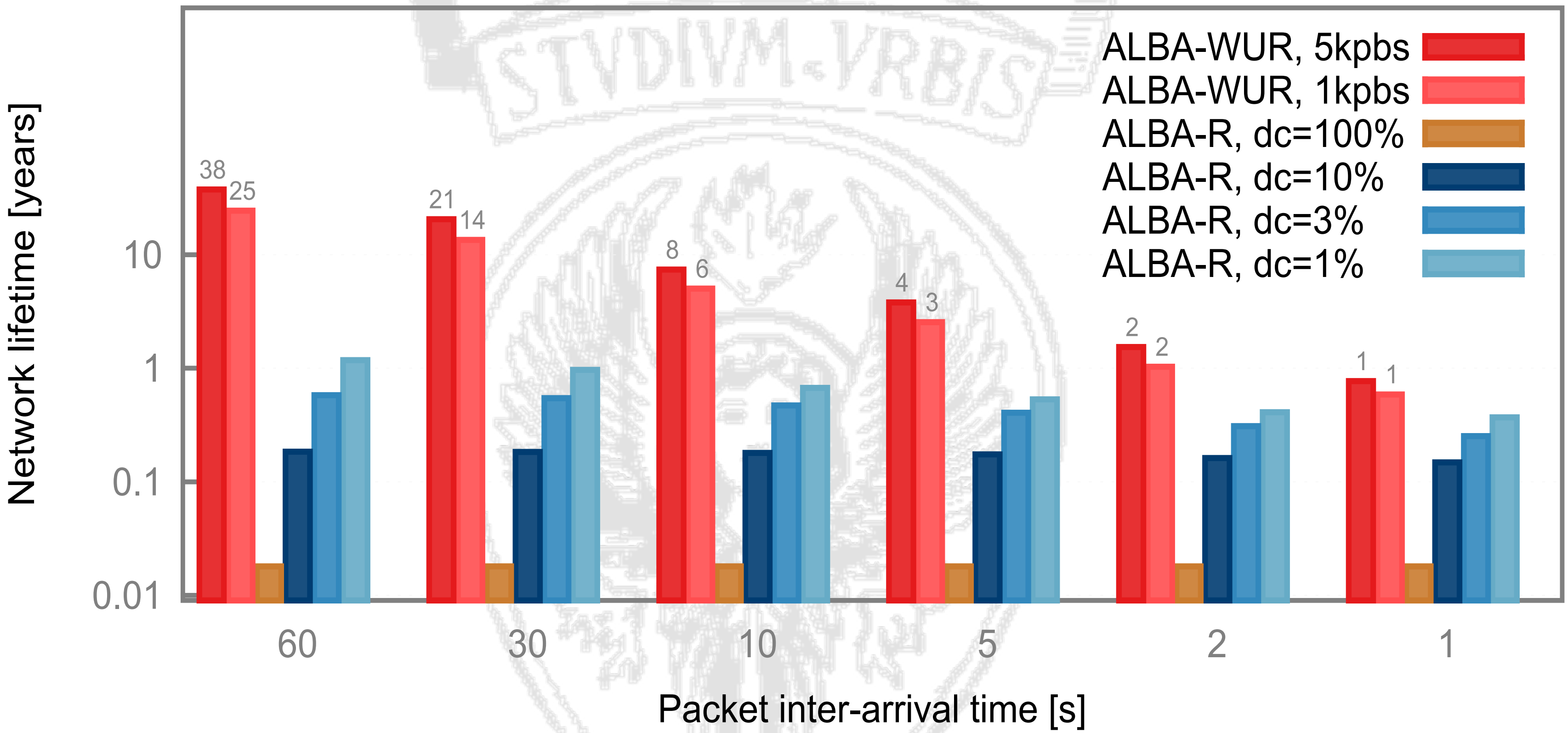
Estimated Network Lifetime



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

Conclusions

- For applications (shorter range/dense deployments) in which wake up radio enabled sensor networks can be adopted WUP-WSNs allow to achieve very long lasting networks at the same time allowing real-time data communications.
- Wake up radio with semantic addresses: Paradigm shift introduced by our recent works
  - + Opens up a lot of research directions
  - + much still to investigate
  - – Technology still under development
- Best students in the class could join the group of PhD and master students working on this reasearch@SENSES!