Towards Energy Efficient LPWANs through Learning-based Multi-hop Routing

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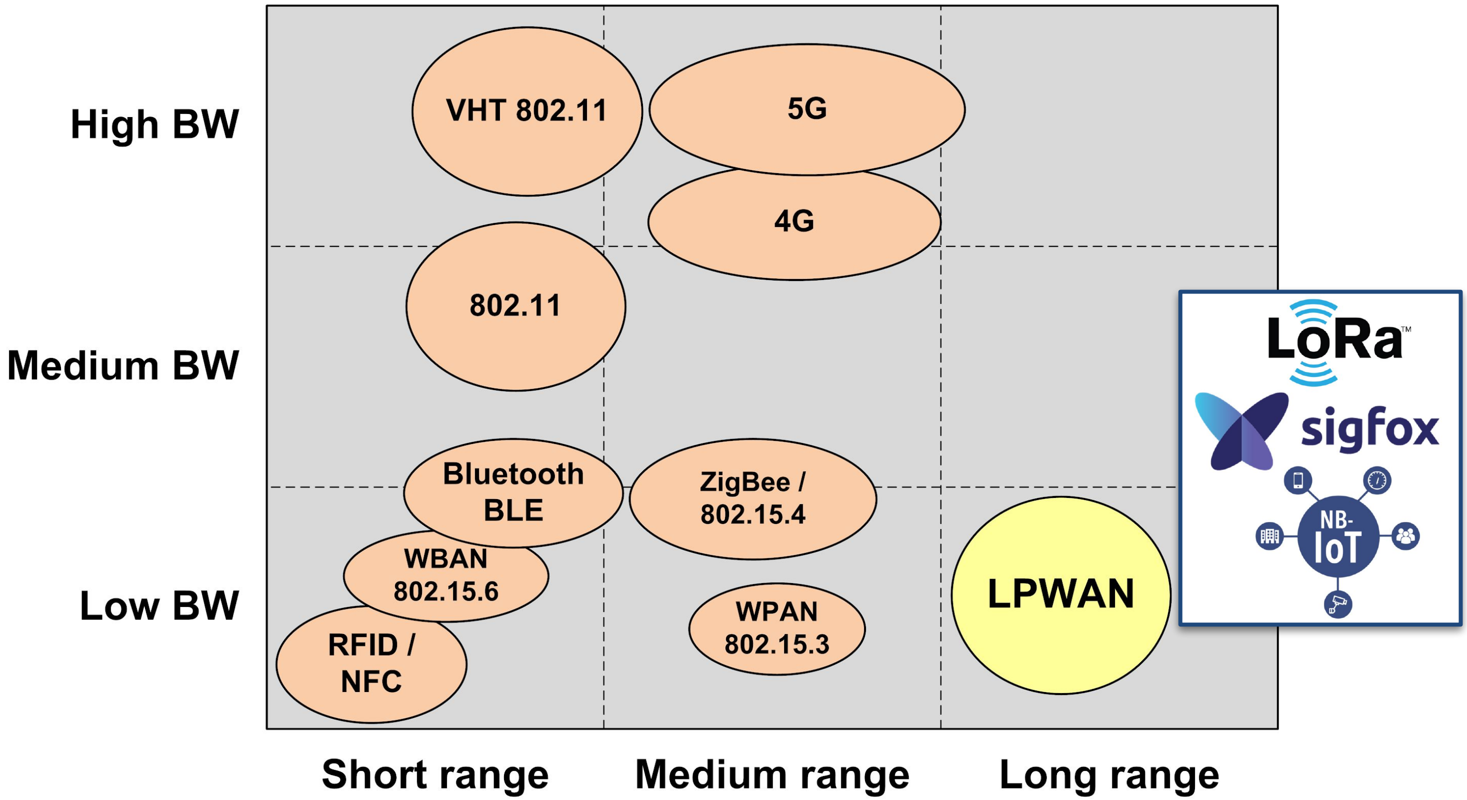
LPWANs in the wireless ecosystem

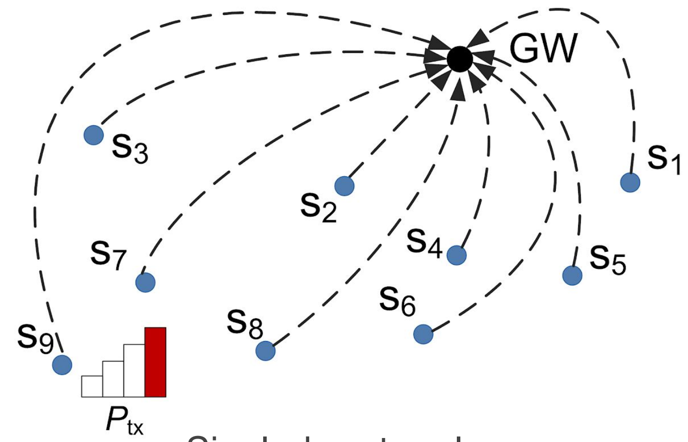


Localization of LPWAN technologies according to range capability and bandwidth required [1]

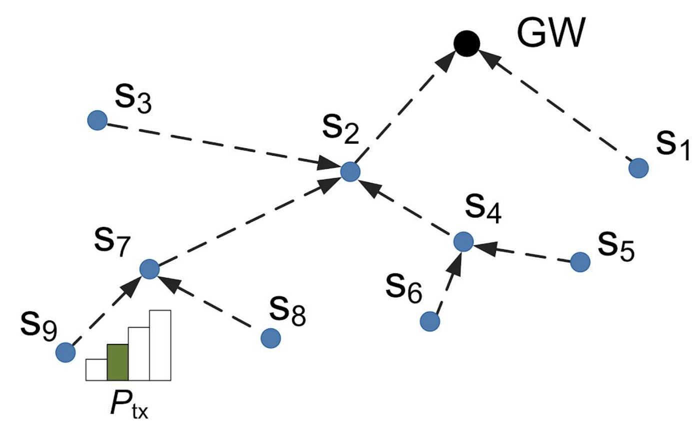
[1] Adame Vázquez, T., Barrachina-Muñoz, S., Bellalta, B., & Bel, A. (2018). HARE: Supporting efficient uplink multi-hop communications in self-organizing LPWANs. *Sensors*, *18*(1), 115.

Routing in LPWANs?

- Most LPWANs rely on single-hop (SH) a.k.a star topologies [2]
  - Robustness ✓
  - Centralized management ✓
  - Simplicity ✓
  - STAs located **far** from the GW **(!?)**
- Multi-hop (MH) on LPWANs
  - Scarce literature on the topic
  - HARE protocol stack [1]
  - MH can extend lifetime [3]



Single-hop topology

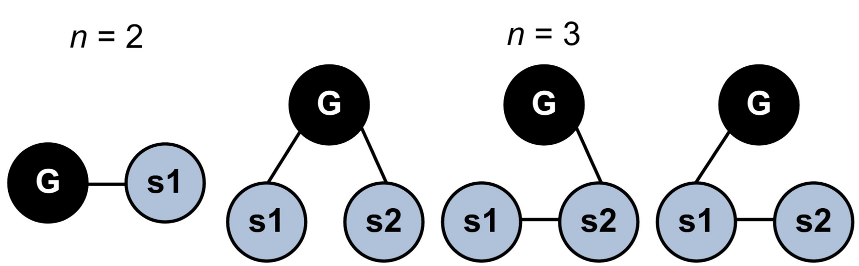


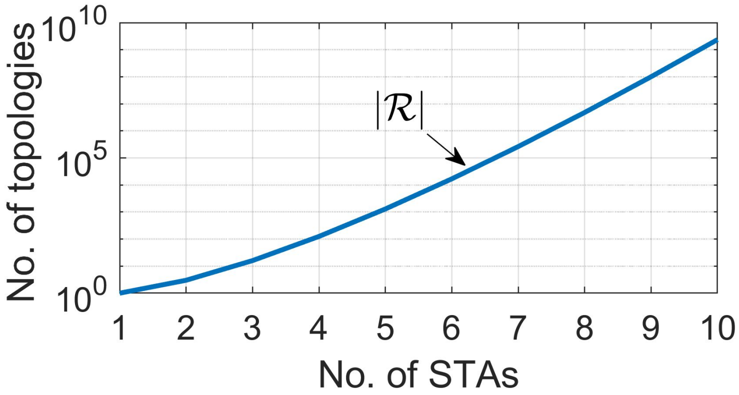
Multi-hop topology

[1] Adame Vázquez, T., Barrachina-Muñoz, S., Bellalta, B., & Bel, A. (2018). HARE: Supporting efficient uplink multi-hop communications in self-organizing LPWANs. *Sensors*, *18*(1), 115.
[2] Laya, A., Kalalas, C., Vazquez-Gallego, F., Alonso, L., & Alonso-Zarate, J. (2016). Goodbye, aloha!. IEEE access, 4, 2029-2044.
[3] Barrachina-Muñoz, S., Bellalta, B., Adame, T., & Bel, A. (2017). Multi-hop communication in the uplink for LPWANs. Computer Networks, 123, 153-168.

How to find efficient MH topologies?

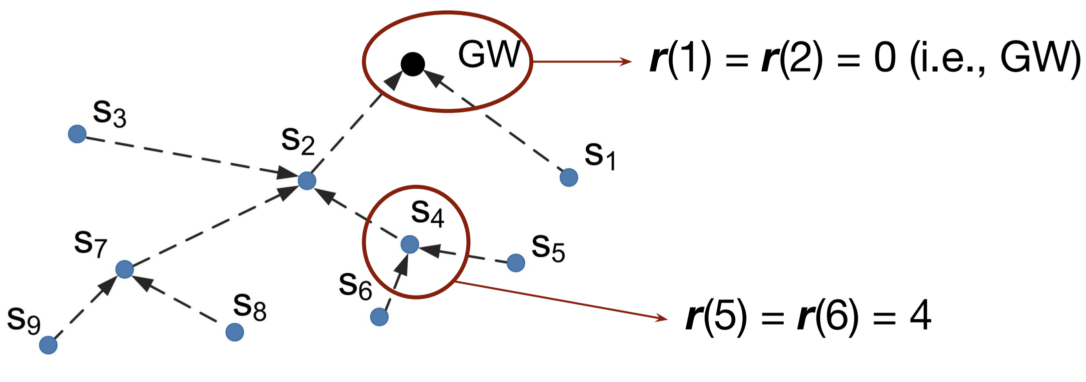
- Links should be **reliable** and **energy-efficient**
- Difficult and fuzzy to determine those links *a priori*
  - Energy consumption depends on **many factors**:
    - Operation modes of the nodes (µProcessor and radio)
    - Network deployment (e.g., location, apps, environment)
  - **Exponential growth** of no. of possible topologies
    - Cayley's formula: $n^{(n-2)}$
    - Exhaustive trial-error may rapidly drain batteries



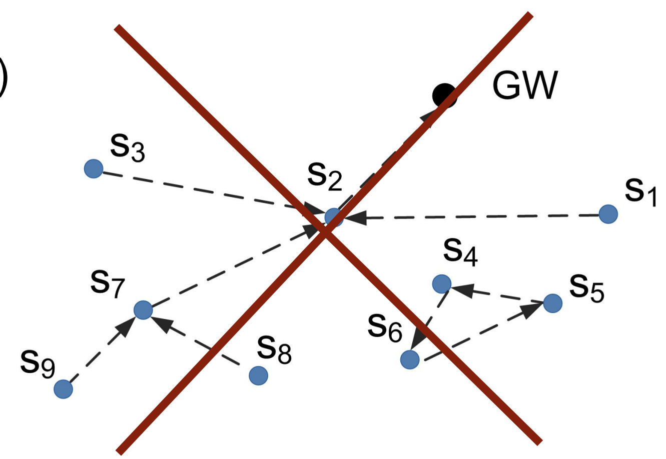


Problem formulation

- **UL routing**: array ***r*** of size *n*-1, where ***r***(*s*) is the parent of *s*
- **Parent**: next-hop of a child STA. GW is always a parent
- **Possible UL routings**: set *R* = {***r***}, s.t., ***r*** is feasible
  - |*R*| is given by Cayley's formula
- **Problem**: maximize lifetime of LPWAN (reduce consumption)
- ***Assumption**: every STA is capable (if required) of SH



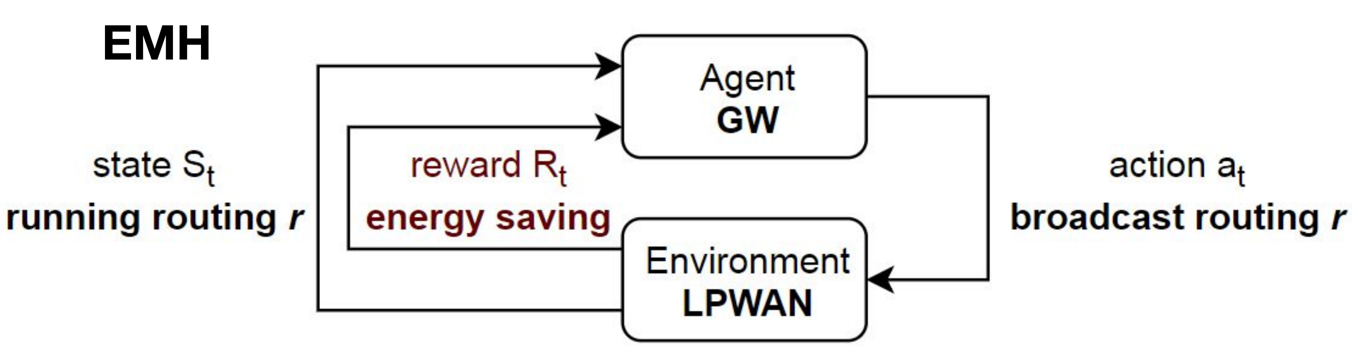
$\vec{r} = (0, 0, 2, 2, 4, 4, 2, 7, 7)$



Unfeasible routing

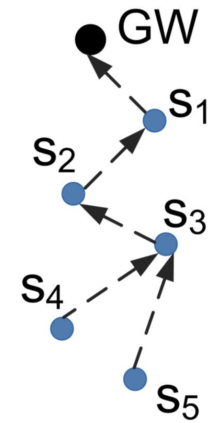
Optimal routing vs. cost of learning

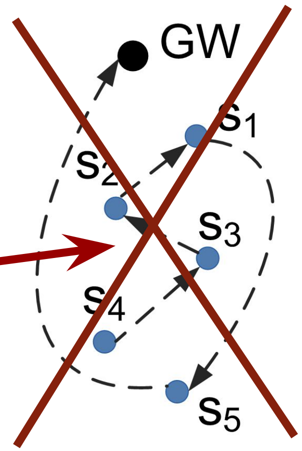
- **Approach**: exploration/exploitation problem
  - Reinforcement learning (RL) multi-armed bandits (MABs)
  - Trade-off:
    - A) **Exploiting**: selecting the best-known routing
    - B) **Exploring**: evaluate unexplored routings
- **Goal**: minimize energy consumption of **bottleneck** STA *b*
  - *b* is the STA that consumes the most energy
  - Lifetime is the operational duration of the bottleneck STA



Epsilon Multi-Hop (EMH) algorithm

- **What**: centralized algorithm for UL routing
- **Operation**: based on MAB's ε-greedy
  - Exploring/exploiting according to ε:
    - $P_{explore} = \varepsilon$, $P_{exploit} = (1 - \varepsilon)$
    - Updating function [4]: $\varepsilon(t) = \varepsilon_o/\sqrt{t}$, with $\varepsilon_o = 1.0$
  - Reward estimation:
    - **Unique**: routings are explored once
    - **Averaged**: $\bar{e}_{\mathrm{b}}(\vec{r_t}) \leftarrow \max_s \frac{1}{K} \sum_{k=1}^{K} e_{s,k}(\vec{r_t})$
  - RSSI-constraint to avoid naive routings
    - Child-parent link (s,s') feasible `iff` $\gamma(s) < \gamma(s')$
    - Narrowed action space for each iteration $A \subseteq R$





Naive routing

[4] P. Auer, N. Cesa-Bianchi, and P. Fischer. Finite-time analysis of the multiarmed bandit problem. Machine learning, 47(2-3):235–256, 2002.

Epsilon Multi-Hop (EMH) algorithm

Algorithm 1: Implementation of EMH in HARE. $\mathcal{U}(\mathcal{A}')$ is a distribution that randomly chooses any unexplored routing in $\mathcal{A}'$ uniformly at random.

Input:
  K `#Number of averaging cycles`
Initialize:
  $t := 0$
  $\hat{p}(\vec{r}) := 0$ for $\forall r \in \mathcal{R}$
  $\epsilon := \epsilon_0$
while *active* **do**
  `#New iteration`
  $\vec{\gamma}_t \leftarrow$ `estimate_rssi() #RSSI from each STA`
  $\mathcal{A}_t \leftarrow \{\vec{r} \in \mathcal{R} \mid \vec{\gamma}_t(s) \geq \vec{\gamma}_t(s') \text{ for } \forall(s, s')\}$ `#Constraint`
  $\mathcal{A}'_t \leftarrow \{\vec{r} \in \mathcal{A} \mid \hat{p}(\vec{r}) = 0\}$ `#Unexplored routings`
  $\vec{r}_t \begin{cases} \text{Explore: } \vec{r} \sim \mathcal{U}({\mathcal{A}'}_t), & \text{with prob. } \epsilon \\ \text{Exploit: } \underset{\vec{r} \in (\mathcal{A}_t \setminus \mathcal{A}'_t)}{\operatorname{argmax}} \hat{p}(\vec{r}), & \text{otherwise} \end{cases}$
  $\bar{e}_{\mathrm{b}}(\vec{r}_t) \leftarrow \max_s \frac{1}{K} \sum_{k=1}^{K} e_{s,k}(\vec{r}_t)$
  $\hat{p}(\vec{r}_t) \leftarrow 1/\bar{e}_{\mathrm{b}}(\vec{r}_t)$
  $\epsilon \leftarrow \epsilon_0/\sqrt{t}$
  $t \leftarrow t + 1$
end

RSSI constraint

ε-greedy action selection

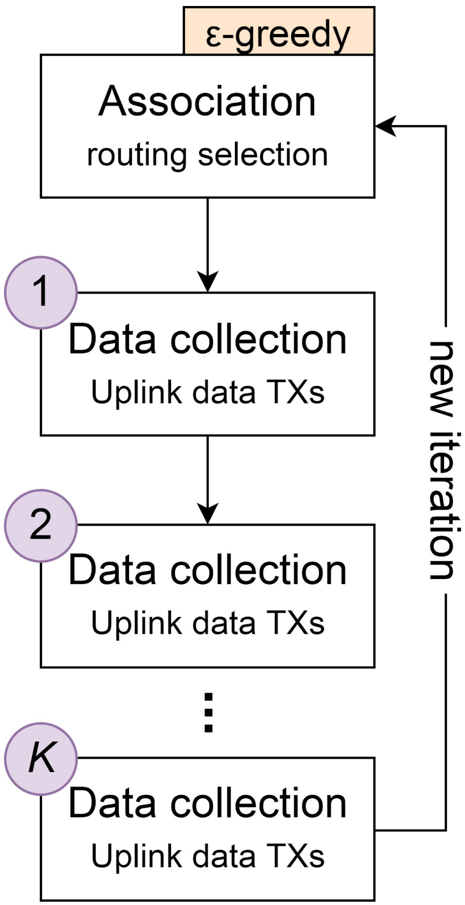
Reward averaging

Update ε

Evaluation testbed

- Zolertia RE-Mote boards [5]
  - Microprocessor ARM Cortex-M3
  - Radio module: TI CC1200 868 MHz
- Contiki 3.0 OS [6]
- X-MAC radio duty cycle [7]
- HARE protocol stack on IEEE 802.15.4 [1]
  - TDMA + CSMA/CA
  - STAs powered by 800 mAh batteries
  - Data packets of 43 bytes every 2 minutes
  - New iteration every K = 10 data collections

HARE + EMH



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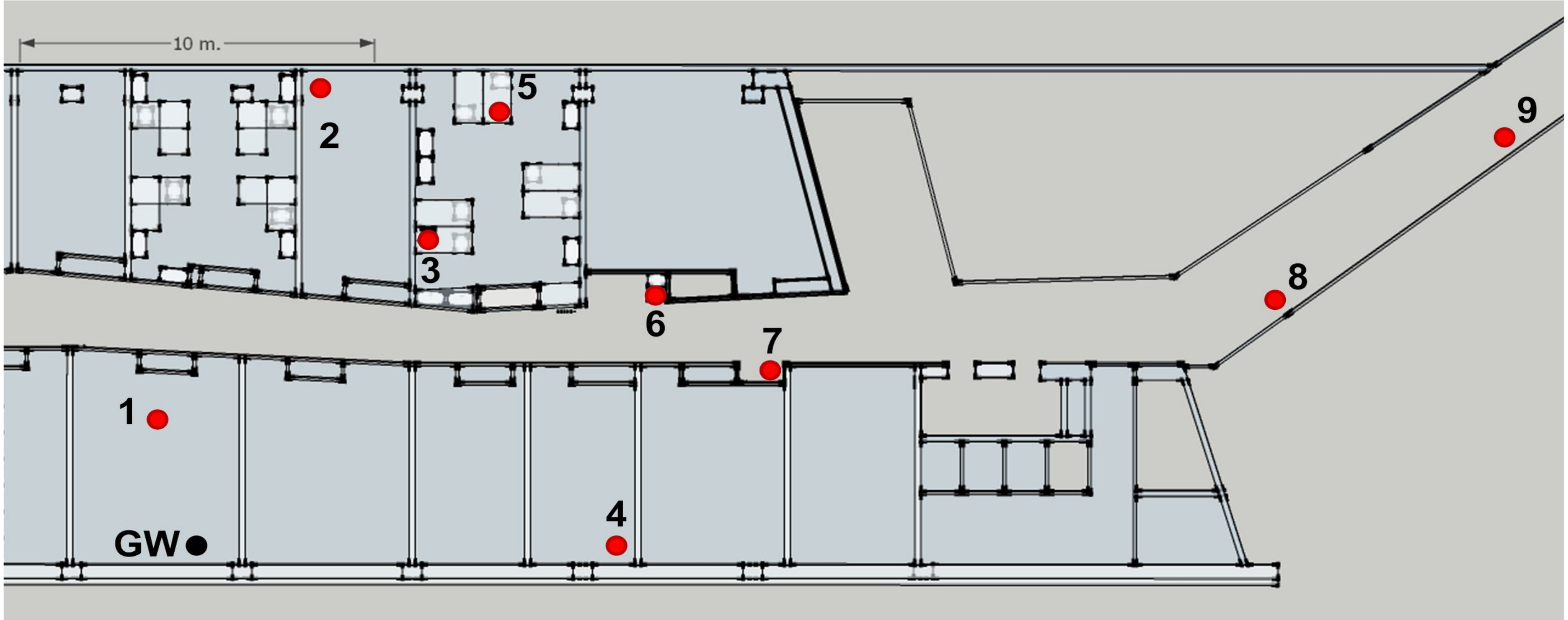
[5] A. Lignan. Zolertia RE-Mote platform. Technical report, Zolertia, 2016. Available online: https://github.com/Zolertia/Resources/raw/master/REMote/ Hardware/Revision(accessed 09/09/2018).
[6] A. Dunkels, B. Gronvall, and T. Voigt. Contiki-a lightweight and flexible operating system for tiny networked sensors. In Local Computer Networks, 2004. 29th Annual IEEE International Conference on, pages 455–462. IEEE, 2004.
[7] M. Buettner, G. Yee, E. Anderson, and R. Han. X-MAC: a short preamble MAC protocol for duty-cycled wireless sensor networks. In Proceedings of the 4th international conference on Embedded networked sensor systems, pages 307–320. ACM, 2006.

Testbed deployment (proof of concept)

- **Indoor** testbed with few (10) nodes
- 2nd floor of UPF Communication campus
- Coverage range ~45 meters
- EMH is **independent** of the environment



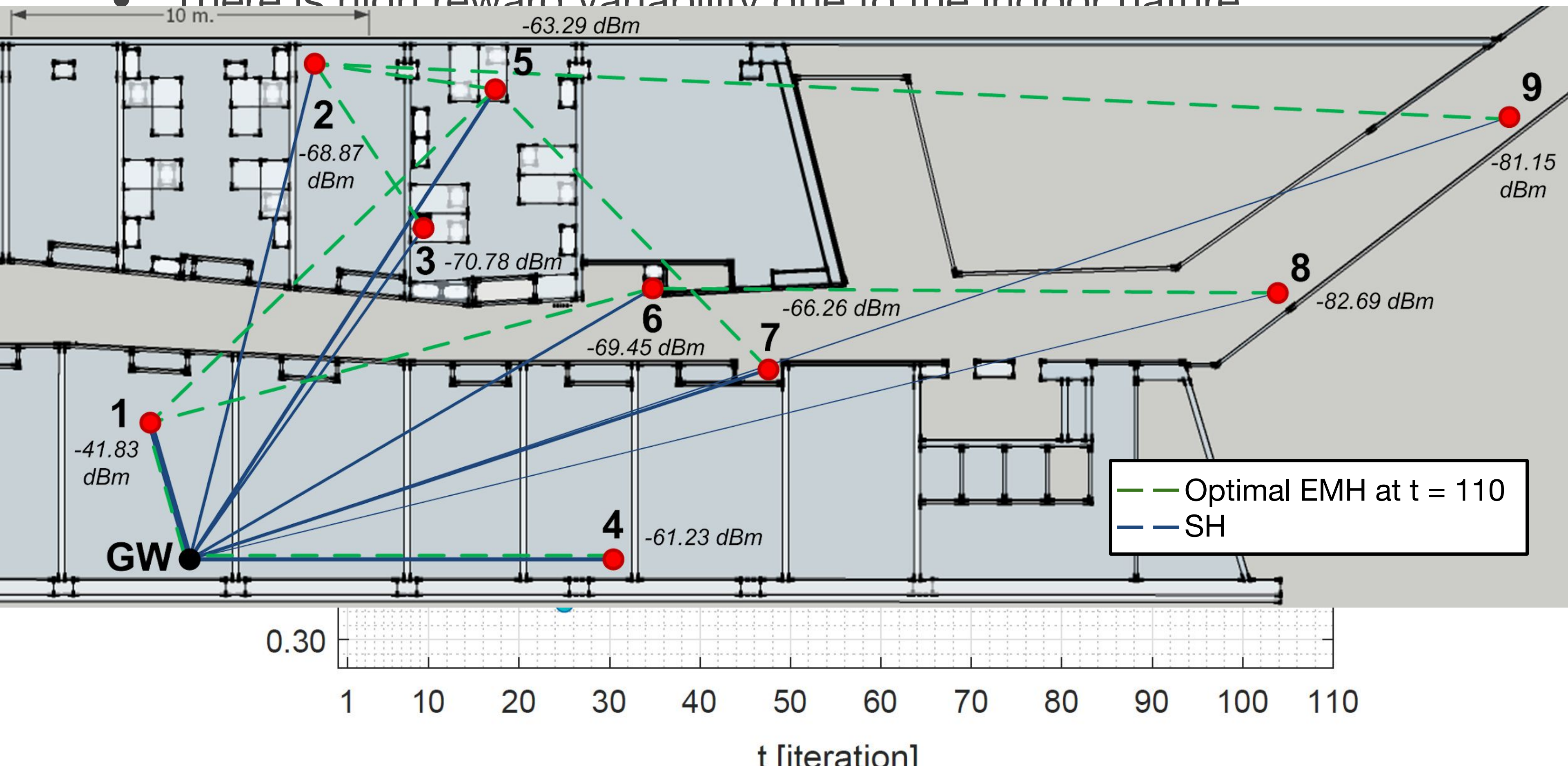
Assessing the energy efficiency

- Energy consumption $e = e_{\mu P} + e_{RM}$ from `energest()` [6]
- Two metrics considered:
  - $\boldsymbol{e_b(t)}$: energy consumed by the bottleneck STA at iteration t
    - Performance of the routing being applied at iteration t
  - $\boldsymbol{\varepsilon(t)}$: cumulated energy of the historic bottleneck STA until t
    - Estimate the lifetime of the network (inv. prop. to $\boldsymbol{\varepsilon}$)
- Goal:
  - To find the routing minimizing $\boldsymbol{e_b(t)}$ …
  - … while considering the finite-horizon constraint by $\boldsymbol{\varepsilon(t)}$
  - Again, exploration vs. exploitation dilemma

[6] A. Dunkels, B. Gronvall, and T. Voigt. Contiki-a lightweight and flexible operating system for tiny networked sensors. In Local Computer Networks, 2004. 29th Annual IEEE International Conference on, pages 455–462. IEEE, 2004.

Cycle bottleneck energy consumption

- $e_b(t)$ decreases with EMH as the experiment progresses
- There is high reward variability due to the indoor nature

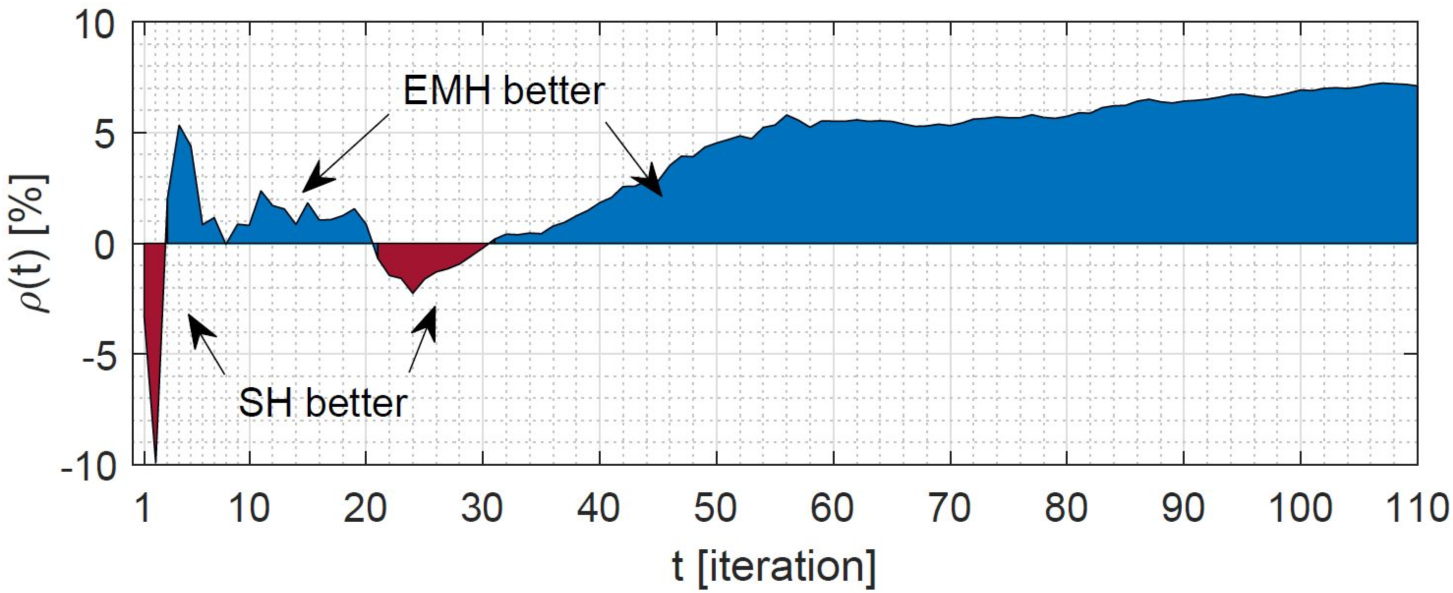


Historic bottleneck energy

- ***ε*(*t*)** maps to the network lifetime
  - ε(*t*)↓ → battery duration↑
- ***ρ*(*t*)** saving ratio at iteration *t*
  - Improvement of EMH vs. SH if *ρ*>0
  - Eventually, increases ~monotonically with *t*

$$\mathcal{E}(t) = \max_s \left(\sum_{t'=1}^{t} \frac{1}{K} \sum_{k=1}^{K} e_{s,k}(\vec{r}_{t'}) \right)$$

$$\rho(t) = \frac{\mathcal{E}_{\mathrm{SH}}(t) - \mathcal{E}_{\mathrm{EMH}}(t)}{\mathcal{E}_{\mathrm{SH}}(t)}$$



Conclusions & next steps

- Lowering energy consumption is critical for LPWANs
  - MH routings in the UL envisioned as promising solution…
  - ...**But**, it is hazardous to predefine static routings
- **EMH** is a centralized RL algorithm for finding efficient routings
  - While the network is normally operating, unexplored routings are stochastically chosen and assessed according to the bottleneck energy payoff function
  - In a HARE testbed with real LPWAN devices, EMH achieves important energy savings with respect to SH
- Future work
  - Evaluating EMH in outdoor and large LPWANs
  - Study the feasibility of more sophisticated RL algorithms

Any questions?

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