Reliability-Driven Deployment in Energy-Harvesting Sensor Networks

Xiaofan Yu[1], Xueyang Song[1], Ludmila Cherkasova[2], Tajana Šimunić Rosing[1]

[1] University of California San Diego
[2] Arm Research

Ubiquitous Internet-of-Things (IoT)

- Around 24.6 billion IoT connections will be established over the globe in 2025[1].

Smart Environment

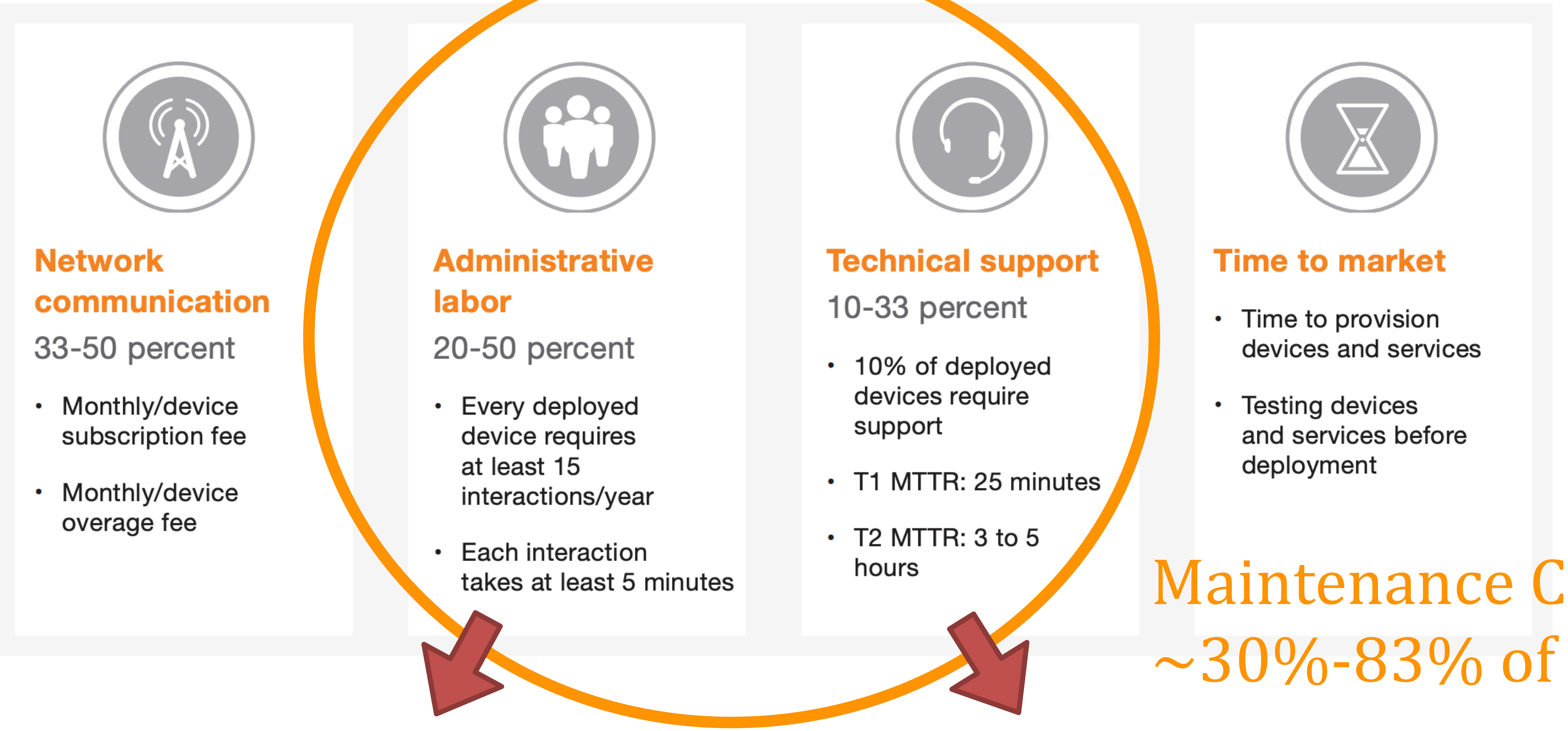
Smart City

Smart Agriculture

Smart Electricity

1. Ericsson Mobility Report, June 2020, https://www.ericsson.com/en/mobility-report/reports.

Operational Costs of IoT[1]



Maintenance Costs!
~30%-83% of total costs!

Managing
Provisioning
Monitoring

Diagnose
Repair
Replacement

1. The Hidden Costs of Delivering IIoT Services, Cisco Jasper, Apr. 2016, https://www.cisco.com/c/dam/m/en_ca/never-better/manufacture/pdfs/hidden-costs-of-delivering-iiot-services-white-paper.pdf.

Energy-Harvesting Sensor Networks

- Lifetime bottleneck can be addressed by energy harvesting techniques
- Energy-Neutral Operation:
  Energy consumption is less than harvested energy income.
- However, all subsystems age and degrade, ultimately requiring repair or replacement

High Performance Wireless Research & Education Network (HPWREN)[1]

Reliability factors are overlooked in previous works!

Harvesting System → Rechargeable Battery → Electronics System

1. HPWREN Brochure, 2003, http://hpwren.ucsd.edu/HPWREN_Brochure_2003/hpwren-brochure-2003.pdf.

Previous Works

- Sensor deployment for energy-harvesting sensor networks
  - [Yang 2016]: The first work adding Energy-Neutral Operation as a constraint
  - [Zhu 2018]: Directional sensors nodes with varying solar-panel sizes

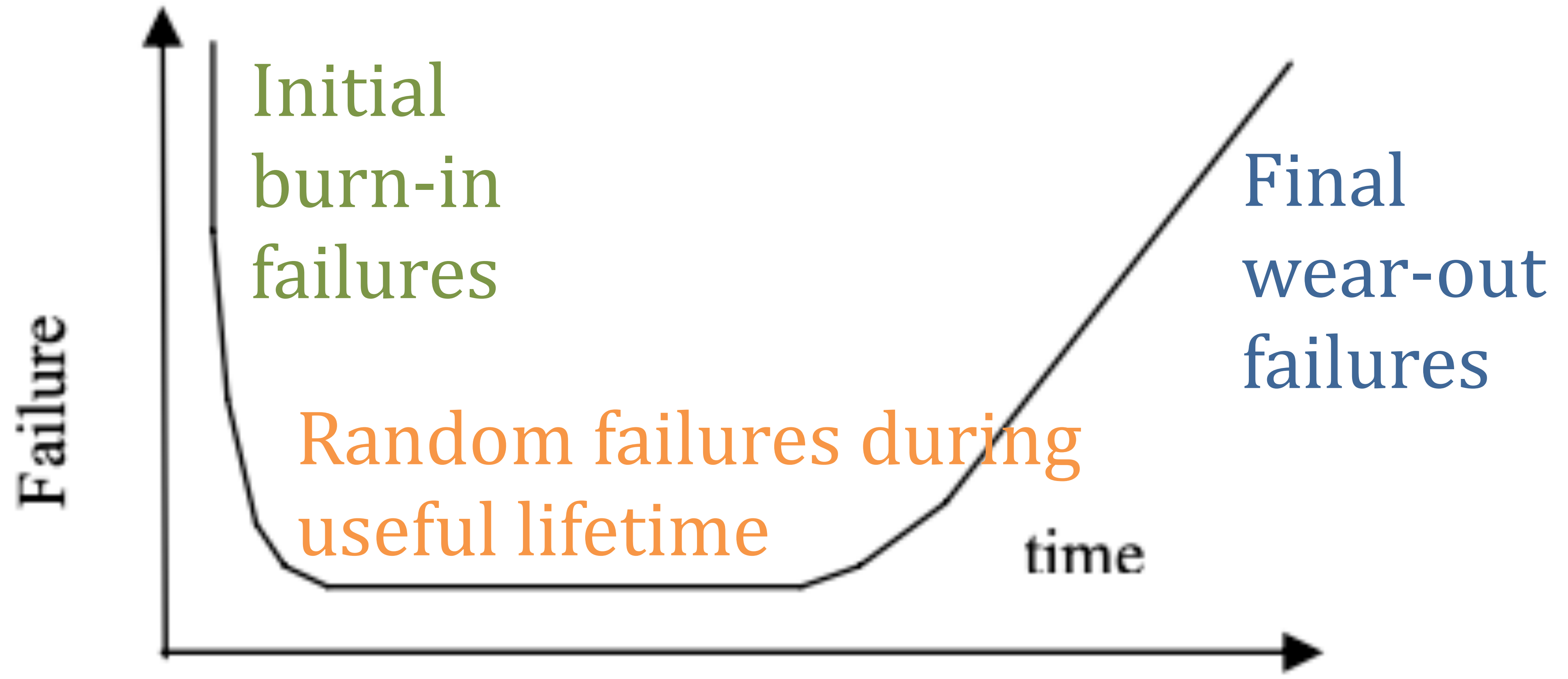
(+) Paved way for sensor deployment problem in energy-harvesting sensor networks

(-) Neither of them considered reliability, which causes striking differences in outdoor environments!

- Reliability-oriented deployment in sensor networks
  - **k-coverage**: each target is covered by at least **k sensors** [Gupta 2016].
  - **m-connectivity**: each node is connected to at least **m other nodes** [Gupta 2016].
  - (-) Redundancy only temporarily mitigates the negative influences of failures!

Reliability Models: Electronics Mean-Time-to-Failure (MTTF) Model

- The bathtub curve characterizes 3 types of devices failures in different stages:
  - Initial burn-in failures <- manufacture imperfections
  - Final wear-out failures <- aging and wear-out
  - Random failures during useful lifetime
    <- failure rates depend on core temperature



The bathtub curve

- Mean-time-to-failure models consider different failure mechanisms [Srinivasan 2004]:
  - Time-dependent dielectric breakdown (TDDB)
  - Negative bias temperature instability (NBTI)
  - Hot Carrier Injection (HCI)

Exponential Temperature Factor!

Share a similar form with different constant c :

$$MTTF = c \exp\left(\frac{E_a}{kT_c}\right)$$

E_a : activation energy, k : Boltzmann's constant, T_c : core temperature

Reliability Models: Battery State-of-Health Model

- State of Charge (SoC): available charge
  State of Health (SoH): aging level
- Lifetime of a rechargeable battery is the time when its SoH reduces from 1 to 0.8 [Xu 2018]

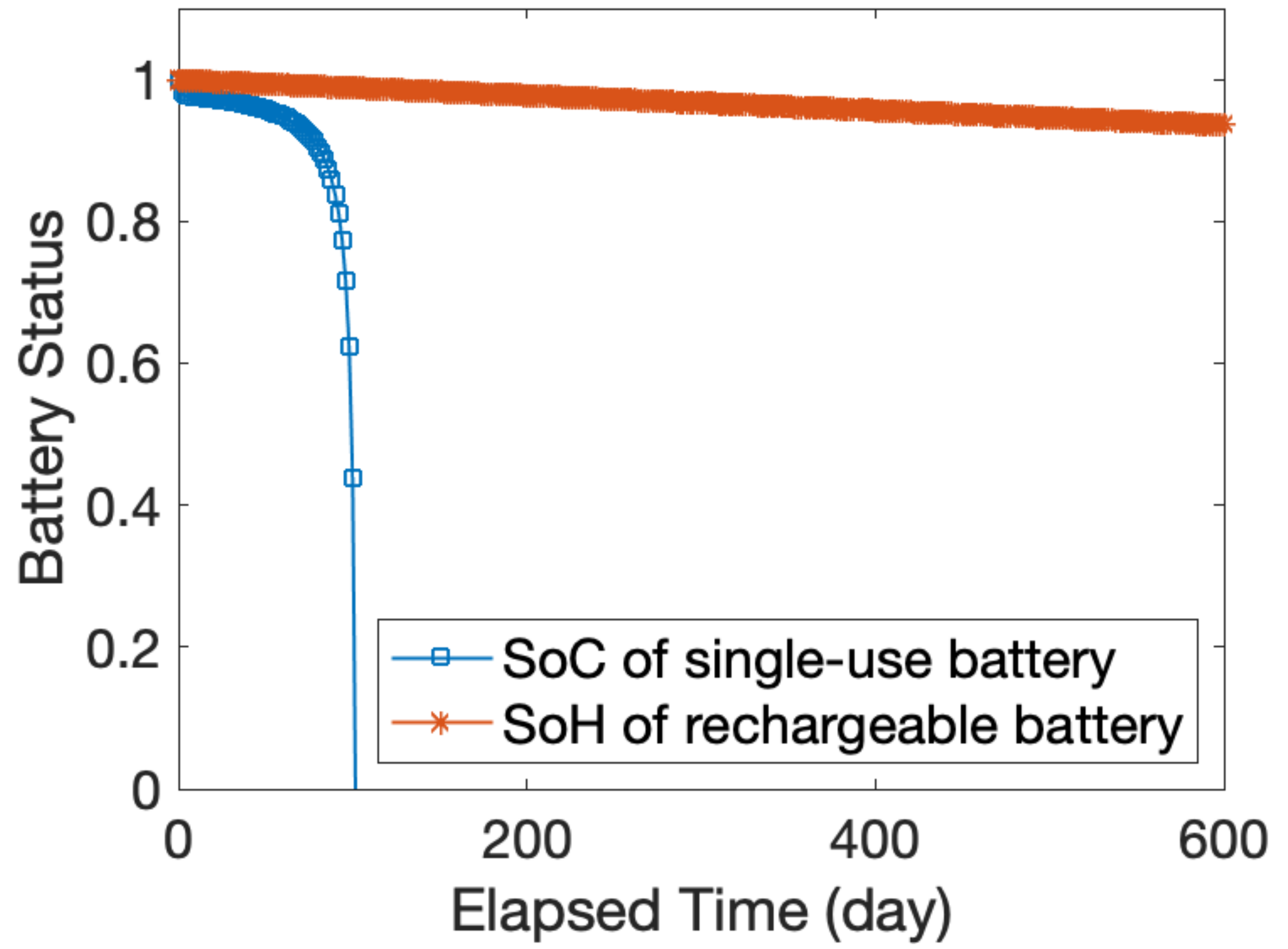
Calendar Aging → Time, temperature, SoC

Cycle Aging → Depth of Discharge

- We focus on calendar aging for long-term SoH [Xu 2018]:

$$SoH(t, T_{cell}) = \exp\left\{ -k_t t \exp\left[k_T T_{ref} \left(1 - \frac{T_{ref}}{T_{cell}} \right) \right] \right\}$$

t : elapsed time, k_t, k_T : predetermined constants, T_{ref} : reference temperature, T_{cell} : cell temperature



1Ah battery, 10 mA current draw, 30 °C

Reliability Models: Core Temperature Conversion

- What we have so far…

Electronics MTTF Model

$$MTTF = c\exp\left(\frac{E_a}{kT_c}\right)$$

Battery SoH Model

$$SoH(t, T_{cell}) = \exp\left\{-k_t t \exp\left[k_T T_{ref}\left(1 - T_{ref}/T_{cell}\right)\right]\right\}$$

- Converting ambient temperature to core temperature [Beneventi 2014]

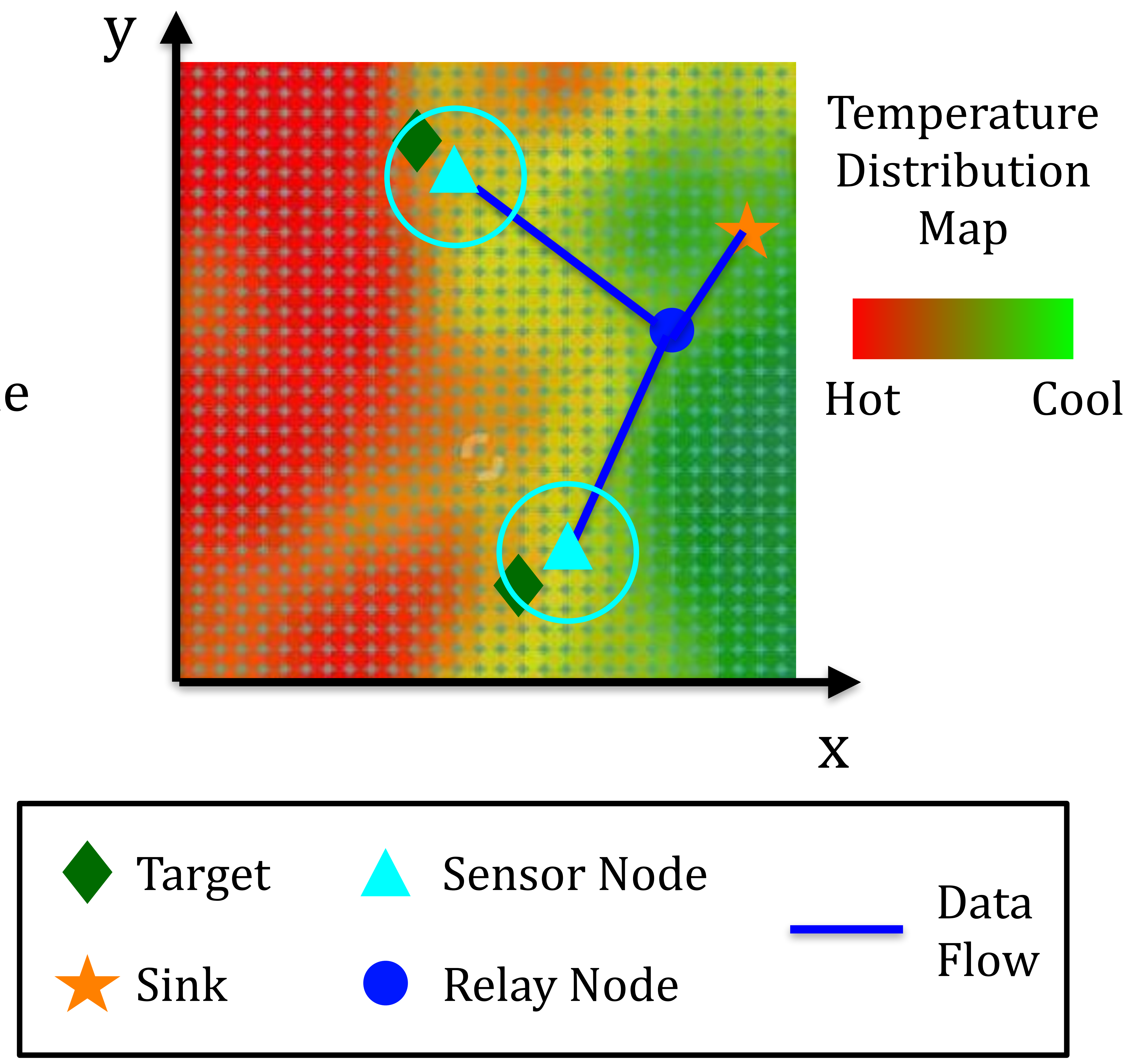
$$T_c[t+1] = AT_c[t] + BP[t] + CT_{amb}[t]\,.$$

- T_c : Core temperature
- P : Average power
- T_{amb} : Ambient temperature
- A, B, C : constant parameters obtained from experiments → Different for different device/battery types!

Reliability-Driven Energy-Harvesting Sensor Deployment

- How to deploy sensor and relay nodes, such that
  - A given set of targets are covered
  - All nodes are connected to the sink
  - Energy-neutral operation is attained at every node
  - Reliability constraints are met at every node
    - Electronics Degradation
    - Rechargeable Battery Degradation

Exponentially accelerated in high-temperature environment!



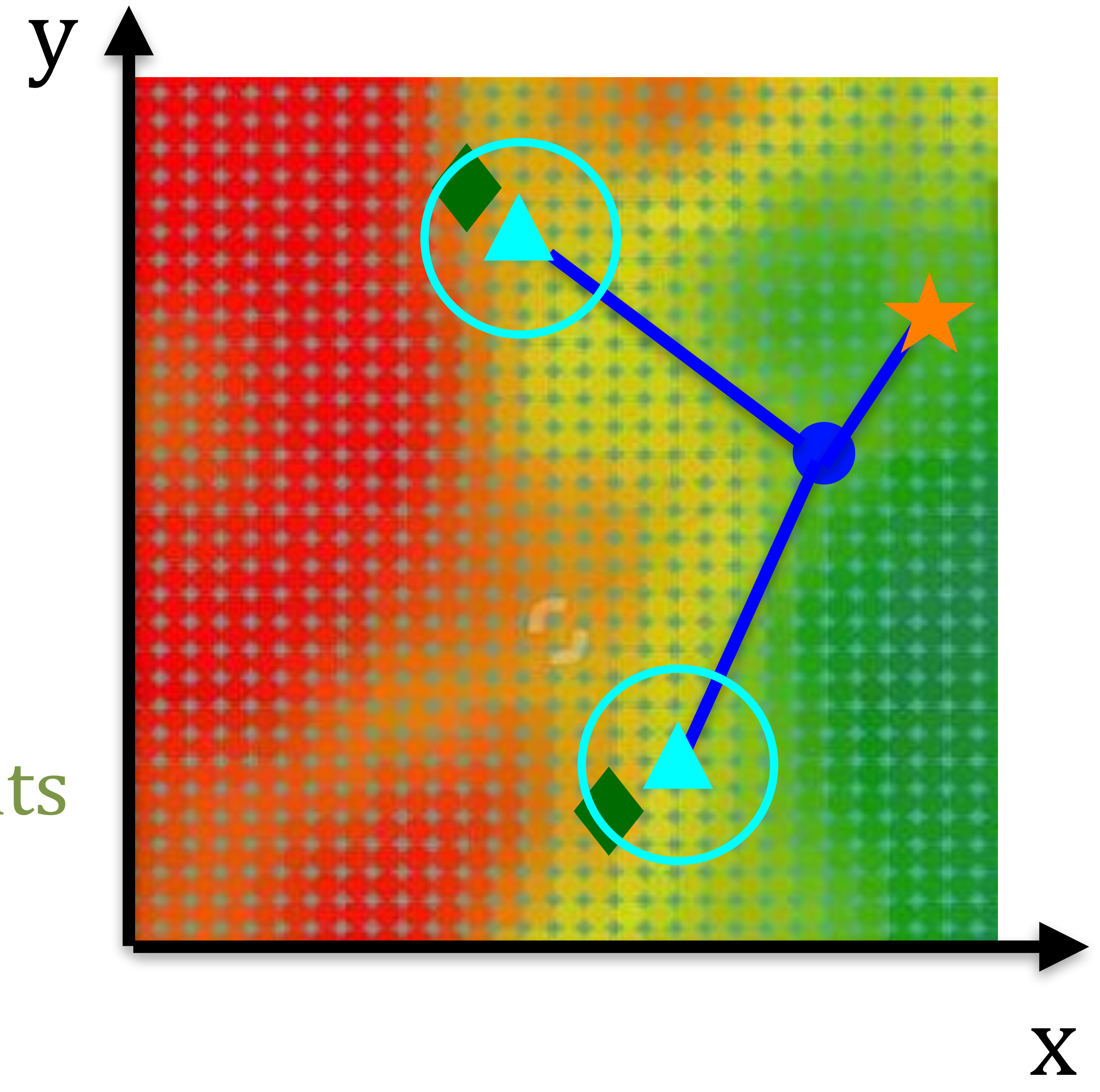
Our Contributions

- To the best of our knowledge, we are the first to integrate state-of-the-art reliability models for energy-harvesting sensor deployment
- We formulate a Mix-Integer Linear Program (MILP) after converting the nonlinear reliability bounds to linear power bounds
- We offer a greedy heuristic named Reliability-driven Two-Stage Heuristic (R-TSH) and evaluate on real-world datasets

Problem Formulation

- Given information
  - a set of targets to monitor
  - a set of candidate grid points
  - solar radiation distribution over the field
  - ambient temperature distribution over the field
- Variables
  - Sensor/relay nodes deployment among the candidate grid points
  - Flow rate between each deployed node
- How to deploy the <u>minimum</u> sensors while satisfying
  - K-coverage
  - Complete connectivity
  - Energy-neutral operation ➡ $P_i \leq R_i$
  - Reliability constraints ➡ $MTTF_i \geq MTTF_{th}$

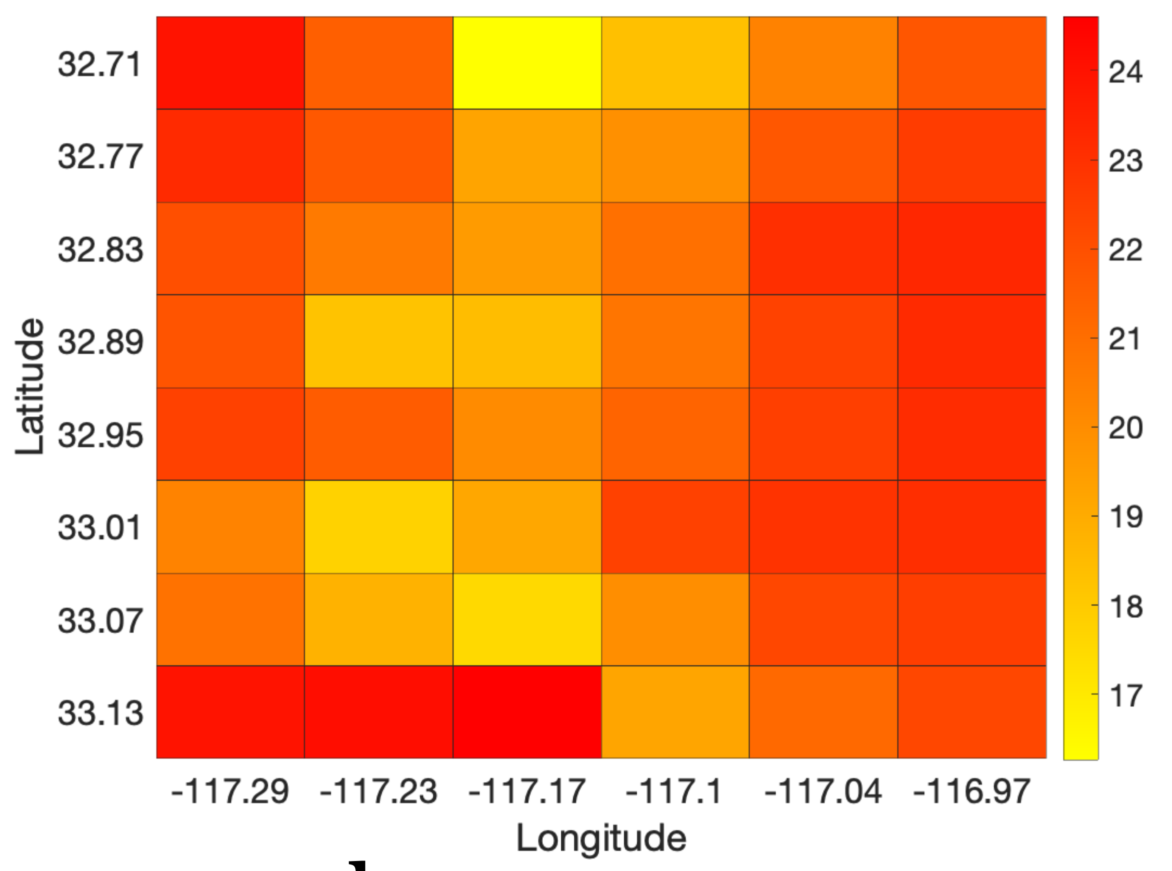
$$SoH_i \geq SoH_{th}$$



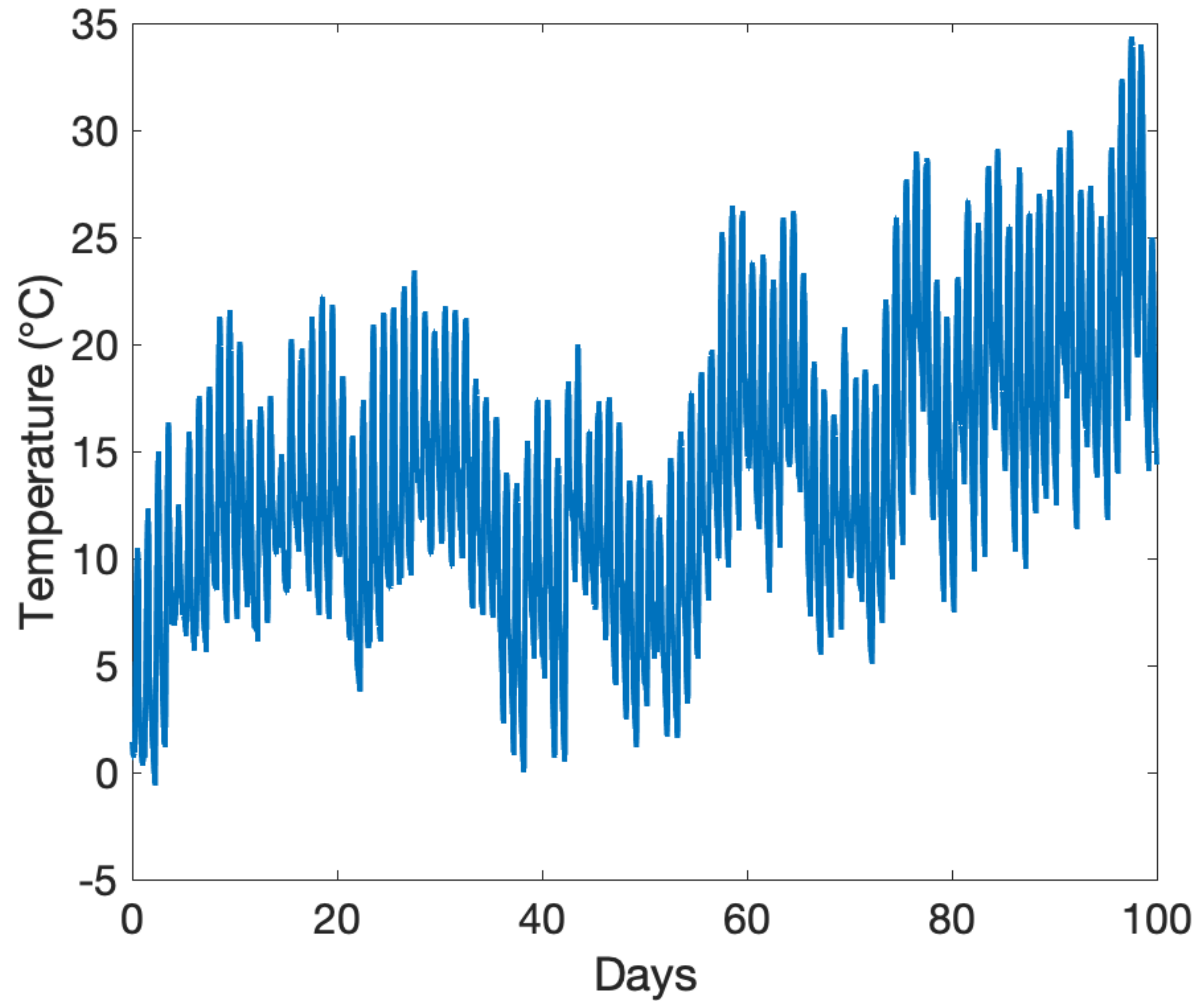
- P_i : Power of device i
- R_i : Harvested energy incoming rate of device i
- $MTTF_i$: Mean time to failure of device i
- $MTTF_{th}$: Predetermined MTTF threshold
- SoH_i: Battery SoH at i after specific time
- SoH_{th}: Predetermined SoH threshold

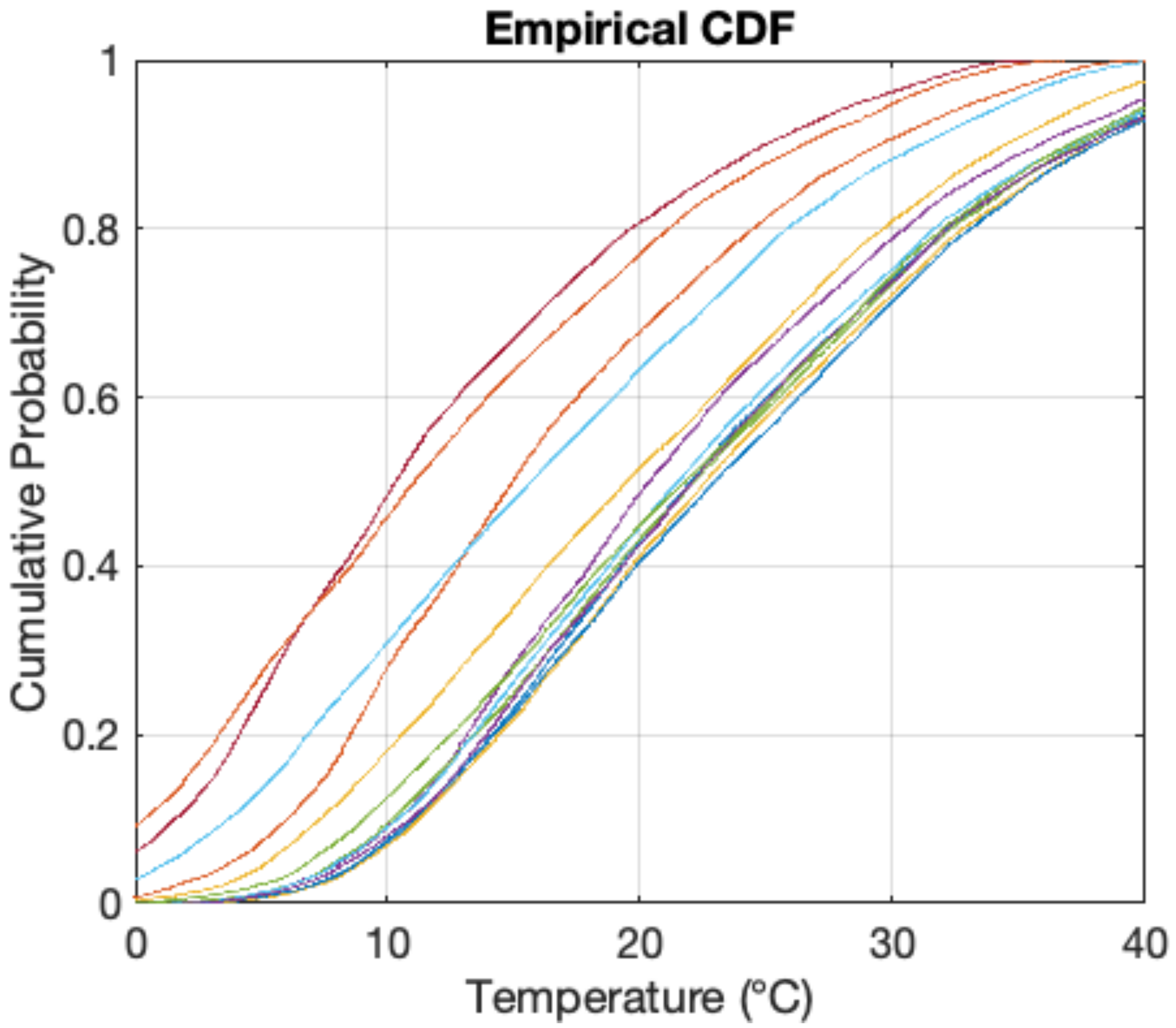
Reliability Metrics under Temperature Variations Over Time

- Spatial temperature variation



- Temporal temperature variation





Cumulative distribution of temperature over time

Our method:
Integral on temperature distribution over time to compute MTTF and battery SoH at each location

Converting Reliability Bounds to Power Bounds

- Recall…

Electronics MTTF Model

$$MTTF = c \exp\left(\frac{E_a}{kT_c}\right)$$

Battery SoH Model

$$SoH(t, T_{cell}) = \exp\left\{-k_t t \exp\left[k_T T_{ref}\left(1 - T_{ref}/T_{cell}\right)\right]\right\}$$

Converting ambient temperature to core temperature

$$T_c[t+1] = AT_c[t] + BP[t] + CT_{amb}[t]\,.$$

- There is an one-to-one mapping between power and MTTF/SoH

Our method:
Use Binary Search Algorithm to locate the corresponding power bounds to meet reliability bounds

$$P_i \leq \min\left\{R_i, P_{SoH,i}, P_{MTTF,i}\right\}$$

- $P_{SoH,i}$: Equivalent power bound for SoH
- $P_{MTTF,i}$: Equivalent power bound for MTTF

Mixed-Integer Linear Program (MILP)

- With the above transformations, the formulated problem turns into a MILP
- NP-complete
- Solved optimally on small cases.

$$\min \sum_{i \in N} x_i \tag{6}$$

subject to

$$\sum_{i \in N} s_i \cdot cov(i,j) \geq K, \quad \forall j \in O \tag{7a}$$

K-coverage

$$s_i \eta G + \sum_{j \in \Gamma_i} f_{ji} = \sum_{j \in \Gamma_i} f_{ij} + f_{iB}, \quad \forall i \in N \tag{7b}$$

$$\sum_{i \in \Gamma_B} f_{iB} = \sum_{i \in N} s_i \eta G \tag{7c}$$

Complete Connectivity

$$s_i \leq x_i, \quad \forall i \in N \tag{7d}$$

$$\sum_{j \in \Gamma_i} f_{ij} \leq \gamma x_i, \quad \forall i \in N \tag{7e}$$

Validation

$$P_i = P_0 + s_i E_s \eta + \sum_{j \in \Gamma_i} \left(P_{tx}(d_{ij}) \frac{f_{ij}}{BW} + P_{rx} \frac{f_{ji}}{BW} \right), \ \forall i \in N \tag{7f}$$

Power Model

$$P_i \leq \min \{R_i, P_{SoH,i}, P_{MTTF,i}\}, \quad \forall i \in N \tag{7g}$$

$$x_i \in \{0,1\}, s_i \in \{0,1\}, \quad \forall i \in N \tag{7h}$$

$$0 \leq f_{ij} \leq \gamma, \quad \forall i \in N, j \in N, i \neq j \tag{7i}$$

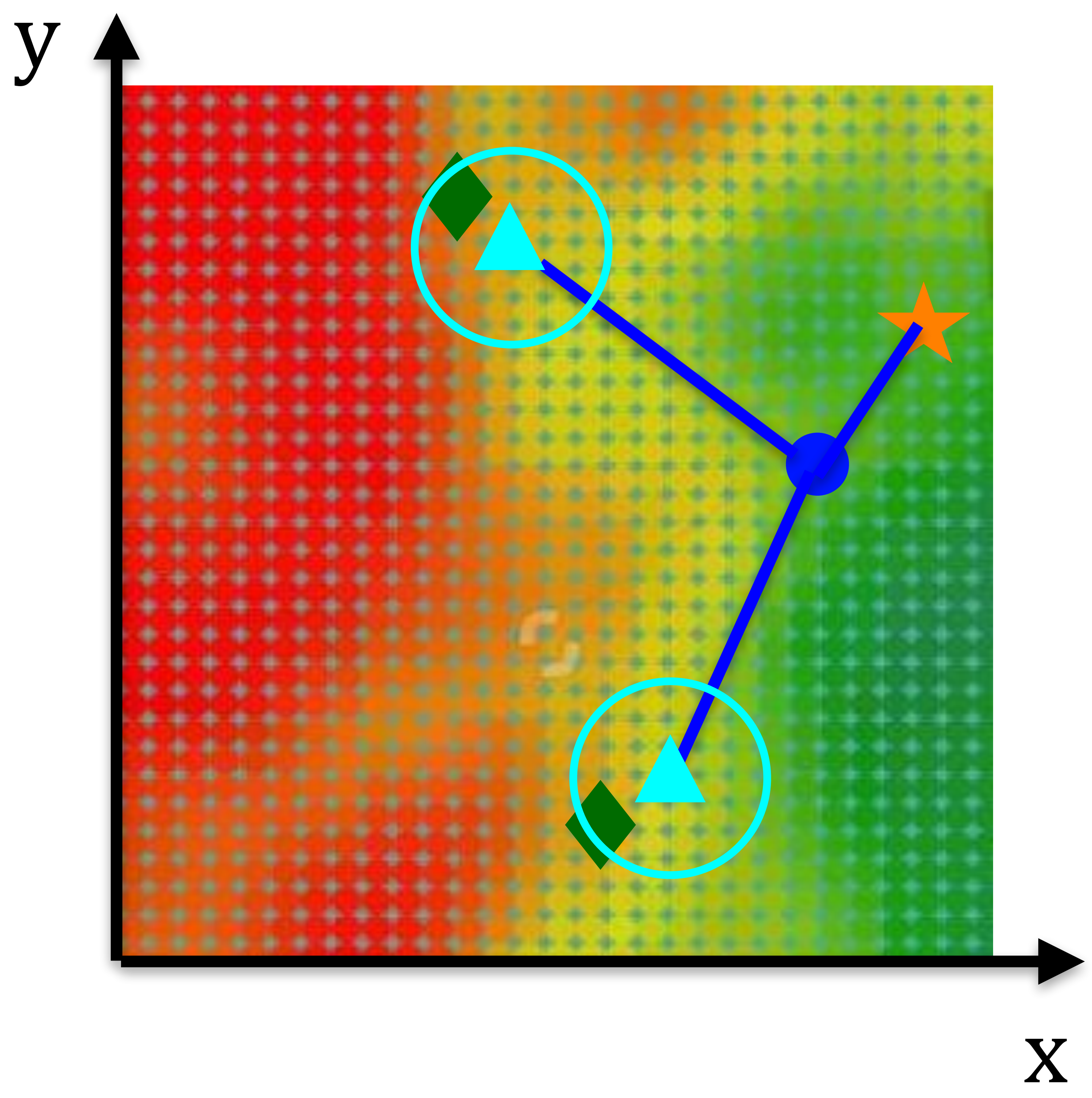
Power & Reliability Constraints

Reliability-Driven Two-Stage Heuristic (R-TSH)

- Due to the NP-completeness of the problem, we propose a greedy heuristic named R-TSH to approximate the optimal solution in large-scale cases.

- Stage 1: Sensor nodes selection
  - Greedily select sensor nodes based on coverage and power/reliability bounds

- Stage 2: Communication path (i.e., relay nodes) selection
  - Construct directed graph and search for the shortest path tree
  - The weights are defined based on number of nodes and power/reliability bounds

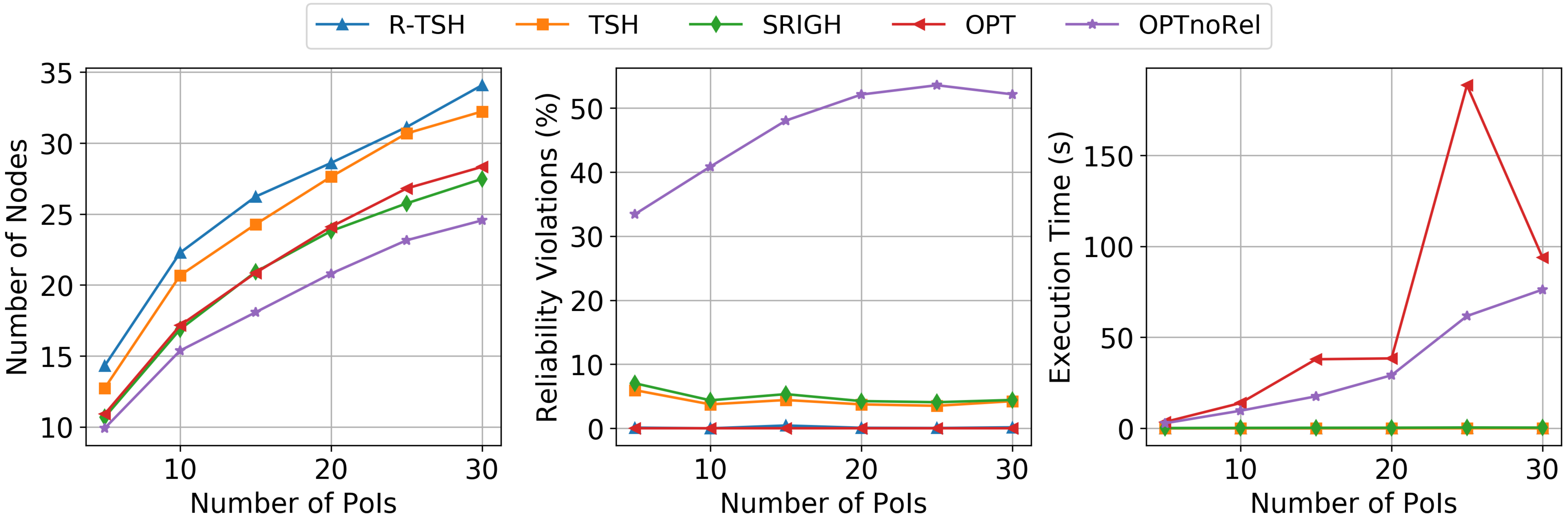


Experimental Setup

- The optimal solver is implemented in CPLEX 12.10 and the heuristic is implemented in MATLAB R2020a[1]
- Linux desktop with Intel Core i7-8700 CPU at 3.2 GHz and 16-GB RAM
- Solar radiation and temperature data from National Solar Radiation Database (NSRDB)[2]
  - 100 km × 100 km, from Jan. 1 2019 to Jan. 1, 2020
- Average results after 10 trials of randomly initialized target locations
- Baselines
  - **TSH** [Zhu 2018]: The original two-stage heuristic
  - **SRIGH** [Zhu 2018]: Sensing- and routing- integrated greedy heuristic
  - **OPT**: The optimal solution with reliability constraints
  - **$\mathbf{OPT_{noRel}}$**: The optimal solution without reliability constraints

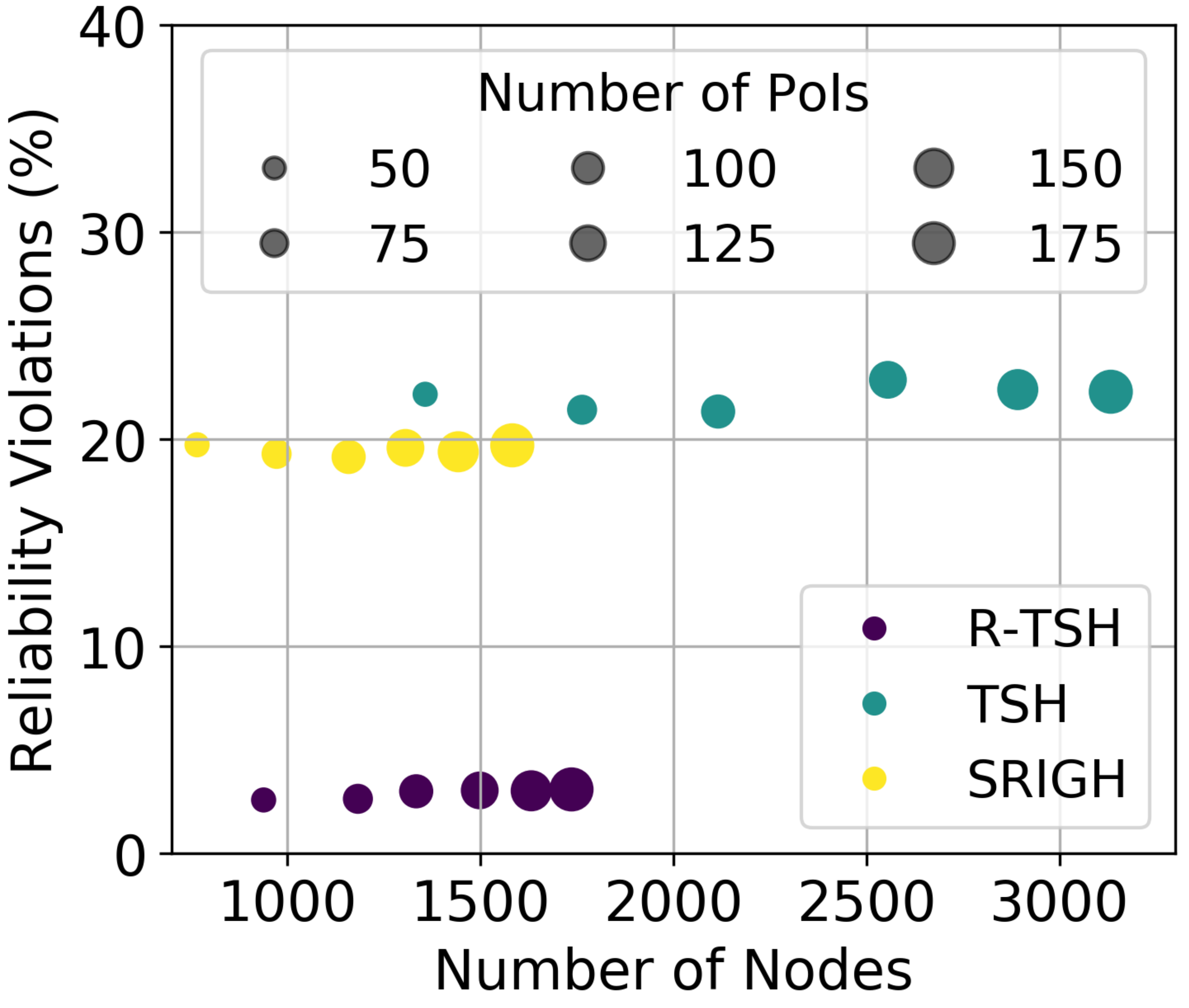
1. Source code is available at https://github.com/Orienfish/EH-deploy.
2. National Solar Radiation Database (NSRDB), https://maps.nrel.gov/nsrdb-viewer/.

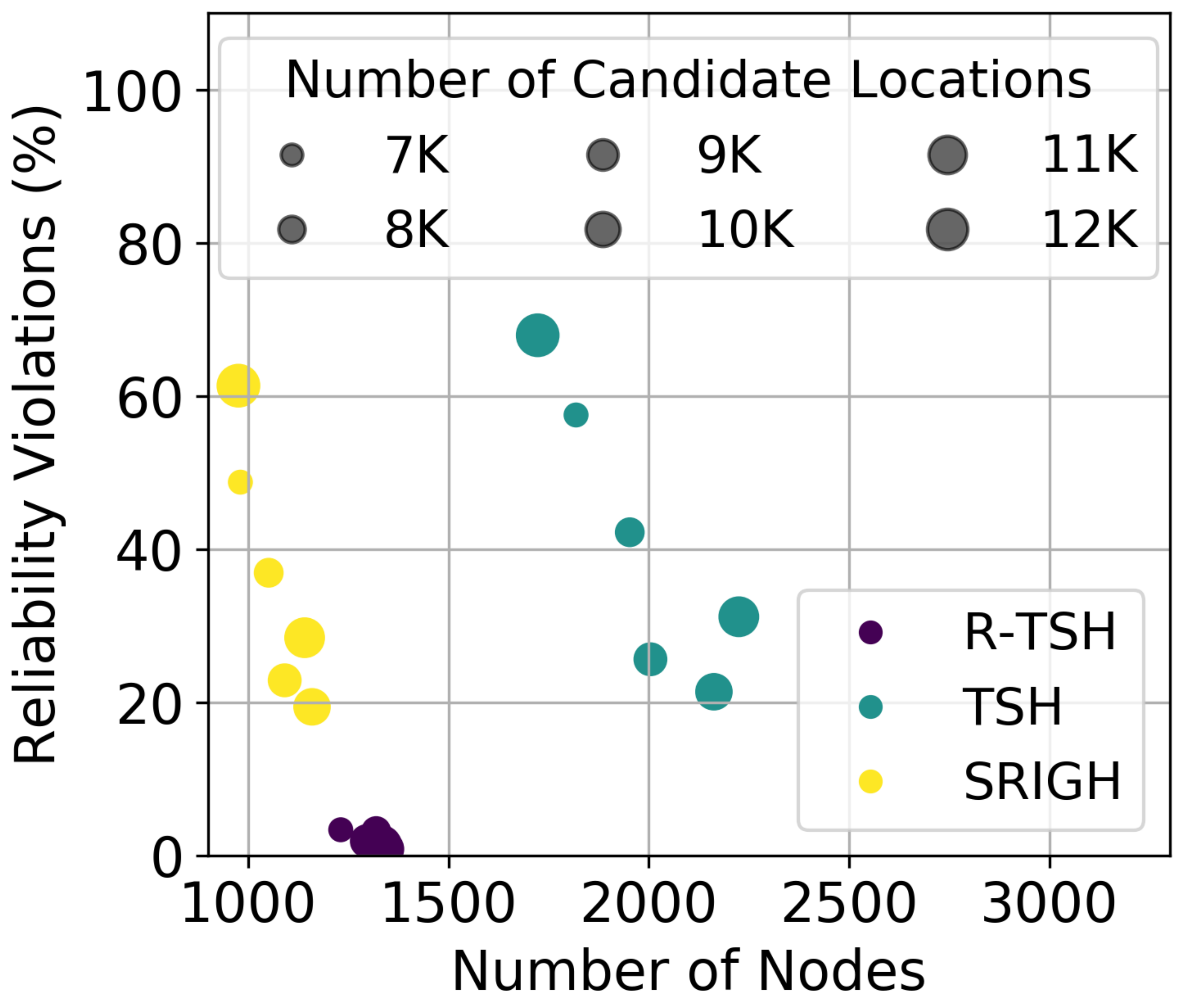
Simulation Results on a Small-Scale Problem



- **OPT vs. OPT$_{noRel}$:** OPT deploys 14% more nodes than OPT$_{noRel}$ but the latter causes more than 30% of reliability violations
- **R-TSH vs. OPT:** R-TSH deploys 20% more nodes than OPT but is 1500x faster
- **R-TSH vs. baseline heuristics:** R-TSH places 6% and 25% more nodes than TSH and SRIGH, respectively, but does not violate any reliability restrictions.

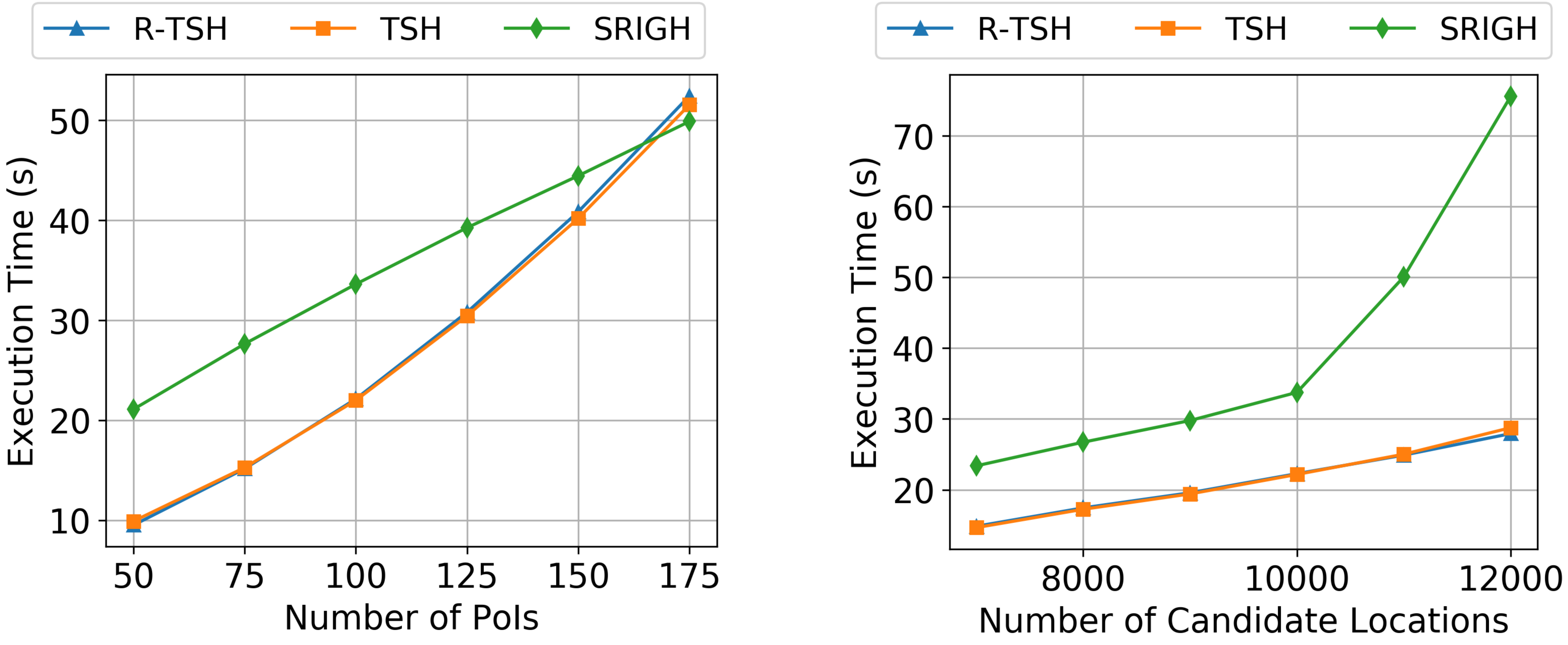
Simulation Results on a Large-Scale Problem





- **Various number of Point-of-Interests (PoIs):** R-TSH places 10% - 20% more nodes than SRIGH but both SRIGH and TSH result in 20% or more reliability violations
- **Various Number of candidate locations:** At the same time, R-TSH consistently keeps the violation rates below 3% while requires 15% - 25% more nodes than SRIGH

Simulation Results on a Large-Scale Problem (Cont.)



- **Execution Time:**
  - R-TSH and TSH share similar execution-time pattern, which scales linearly when we increase the number of candidate locations.
  - SRIGH presents a different pattern that scales linearly when we increase the number of PoIs.

Conclusion

- We integrate state-of-the-art reliability models to sensor deployment in energy-harvesting sensor networks
  - We use electronics MTTF model and battery SoH model, both incorporating the exponential temperature factor
- We formulate a sensor deployment problem optimizing for minimum nodes while satisfying (i) k-coverage, (ii) complete connectivity, (iii) energy-neutral operation, (iv) reliability constraints
- We devise a Reliability-Driven Two-Stage Heuristic (R-TSH) to approximate the optimal solution in large-scale problems
- Simulation results show that our heuristic meets all reliability constraints with only 20% more sensors than the optimal solution in a small field
- Compared to state-of-the-art heuristics, R-TSH avoids 20% - 80% of reliability violations with a comparable number of nodes and execution time.

Thanks!

Questions?

System Energy Efficiency Lab

seelab.ucsd.edu

References

- Yang, Changlin, and Kwan-Wu Chin. "On nodes placement in energy harvesting wireless sensor networks for coverage and connectivity." *IEEE Transactions on Industrial Informatics* 13.1 (2016): 27-36.
- Zhu, Xiaojian, Jun Li, and MengChu Zhou. "Optimal deployment of energy-harvesting directional sensor networks for target coverage." *IEEE Systems Journal* 13.1 (2018): 377-388.
- Gupta, Suneet Kumar, Pratyay Kuila, and Prasanta K. Jana. "Genetic algorithm approach for k-coverage and m-connected node placement in target based wireless sensor networks." *Computers & Electrical Engineering* 56 (2016): 544-556.
- Beneventi, Francesco, et al. "An effective gray-box identification procedure for multicore thermal modeling." *IEEE Transactions on Computers* 63.5 (2012): 1097-1110.
- Srinivasan, Jayanth, et al. "The case for lifetime reliability-aware microprocessors." *ACM SIGARCH Computer Architecture News* 32.2 (2004): 276.
- Xu, Bolun, et al. "Modeling of lithium-ion battery degradation for cell life assessment." *IEEE Transactions on Smart Grid* 9.2 (2016): 1131-1140.