Optimizing Sensor Deployment and Maintenance Costs for Large-Scale Environmental Monitoring

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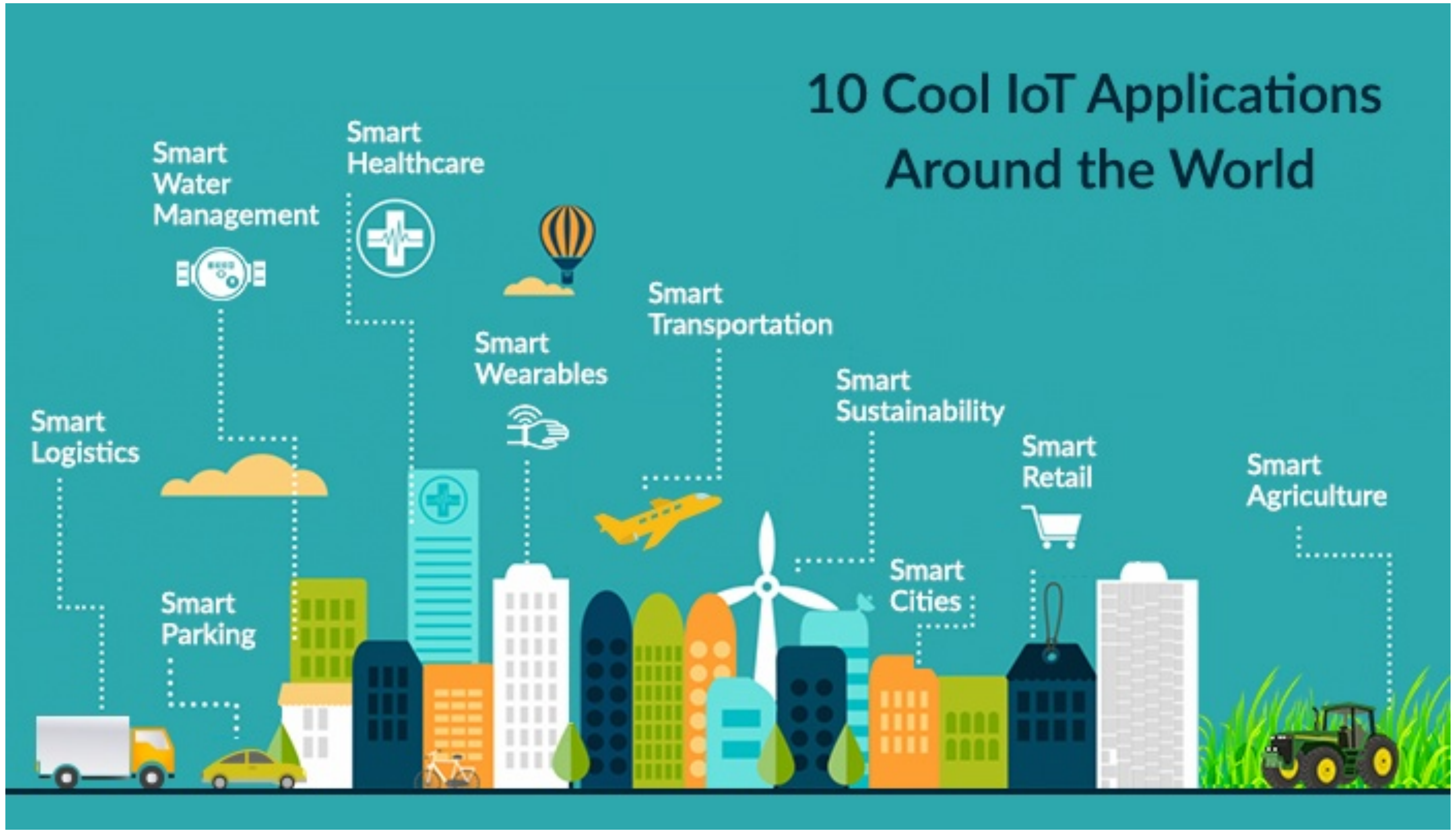
Ubiquitous Internet-of-Things (IoT)

- Around 24.6 billion IoT connections will be established over the globe in 2025, 23% of which is taken by wide-area IoT[1].



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1. Ericsson Mobility Report, Jun 2020, https://www.ericsson.com/en/mobility-report/reports.
2. Figure source: https://www.clariontech.com/blog/10-cool-iot-applications-around-the-world.

Large-Scale Environmental Monitoring

Forest fire monitoring

Wildlife tracking

Air pollution monitoring

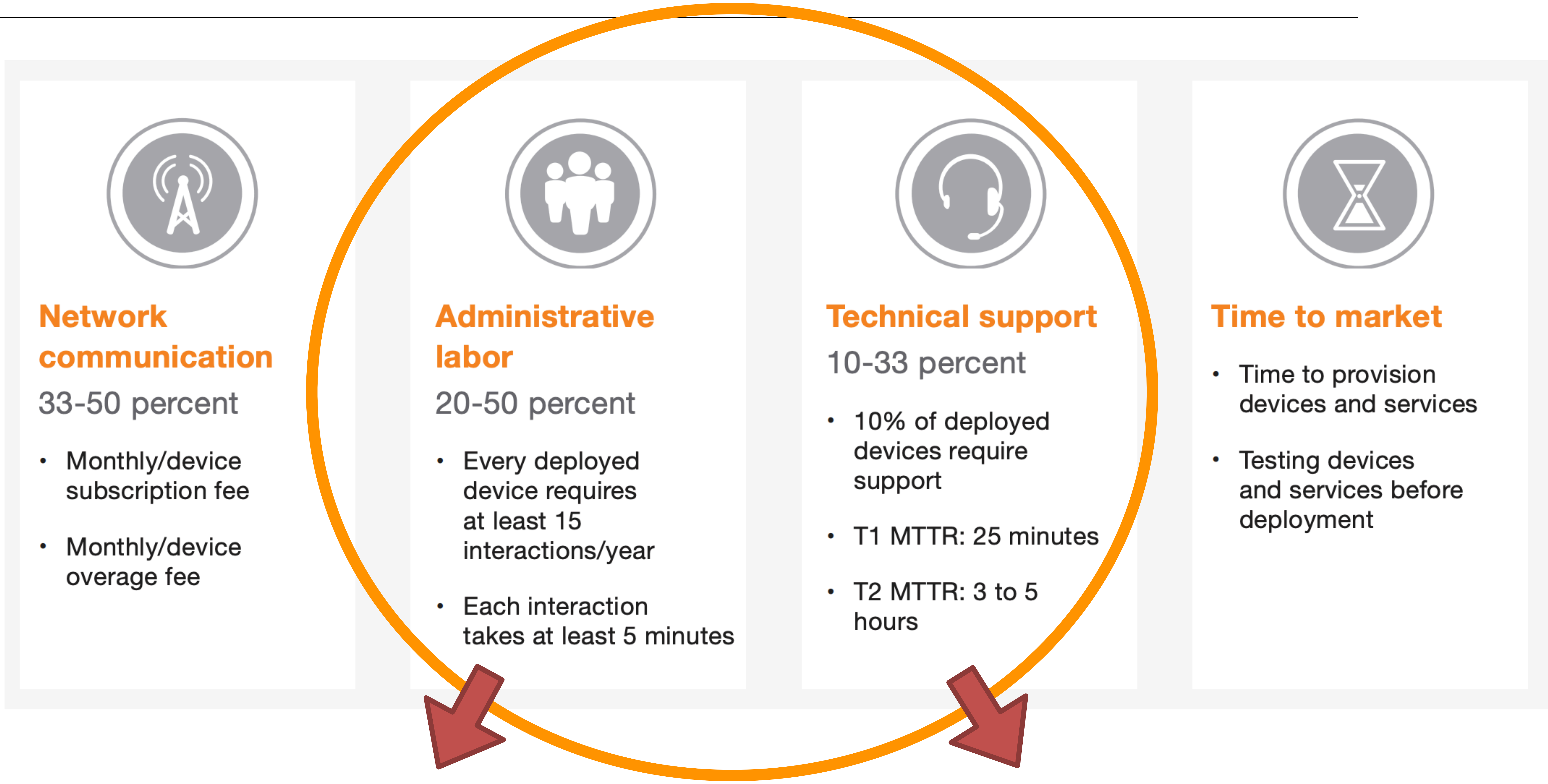
Water quality monitoring

- Large coverage
- Unstable connectivity
- Resource- and energy-constrained devices
- Huge maintenance cost → Disregarded by previous works!

Hidden Costs of IoT[2]

30-83%, up to 3.2M$/year for 100k devices

- Installation costs are one-time costs, including design, implementation, manufacturing, etc.
- Maintenance costs are recurring costs



Managing
Provisioning
Monitoring

Diagnose
Repair
Replacement

2. 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.

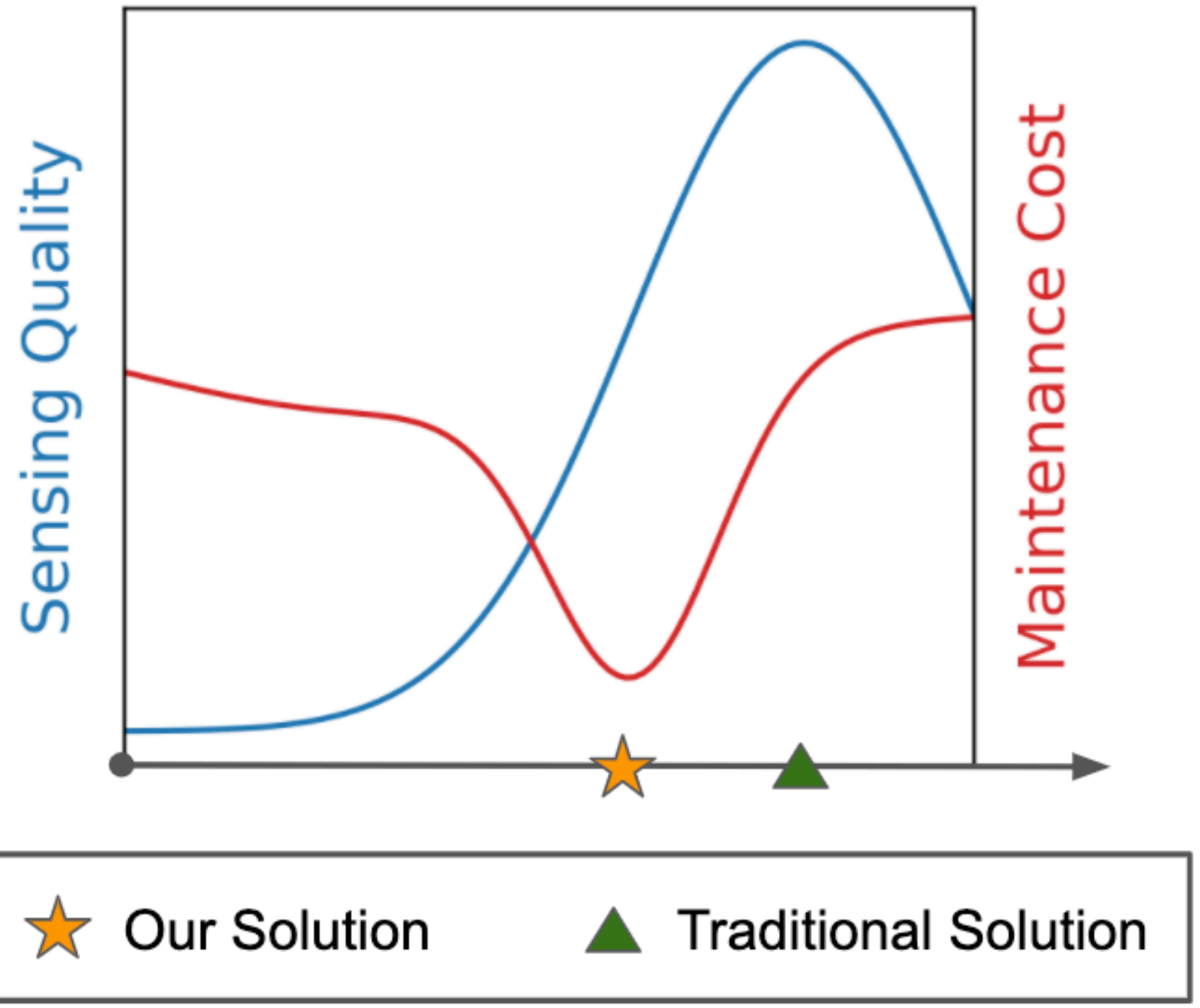
How to Manage Maintenance Cost?

- We aim at preventively minimizing the maintenance cost from the very first step of sensor deployment

How to model maintenance cost?

- Software failures — Bugs, OS crashes
- Link failures — Temporal inavailability
- **Hardware failures** — Short circuit

{ Electronics Failures → Device Replacement
{ Battery Depletion → Battery Replacement

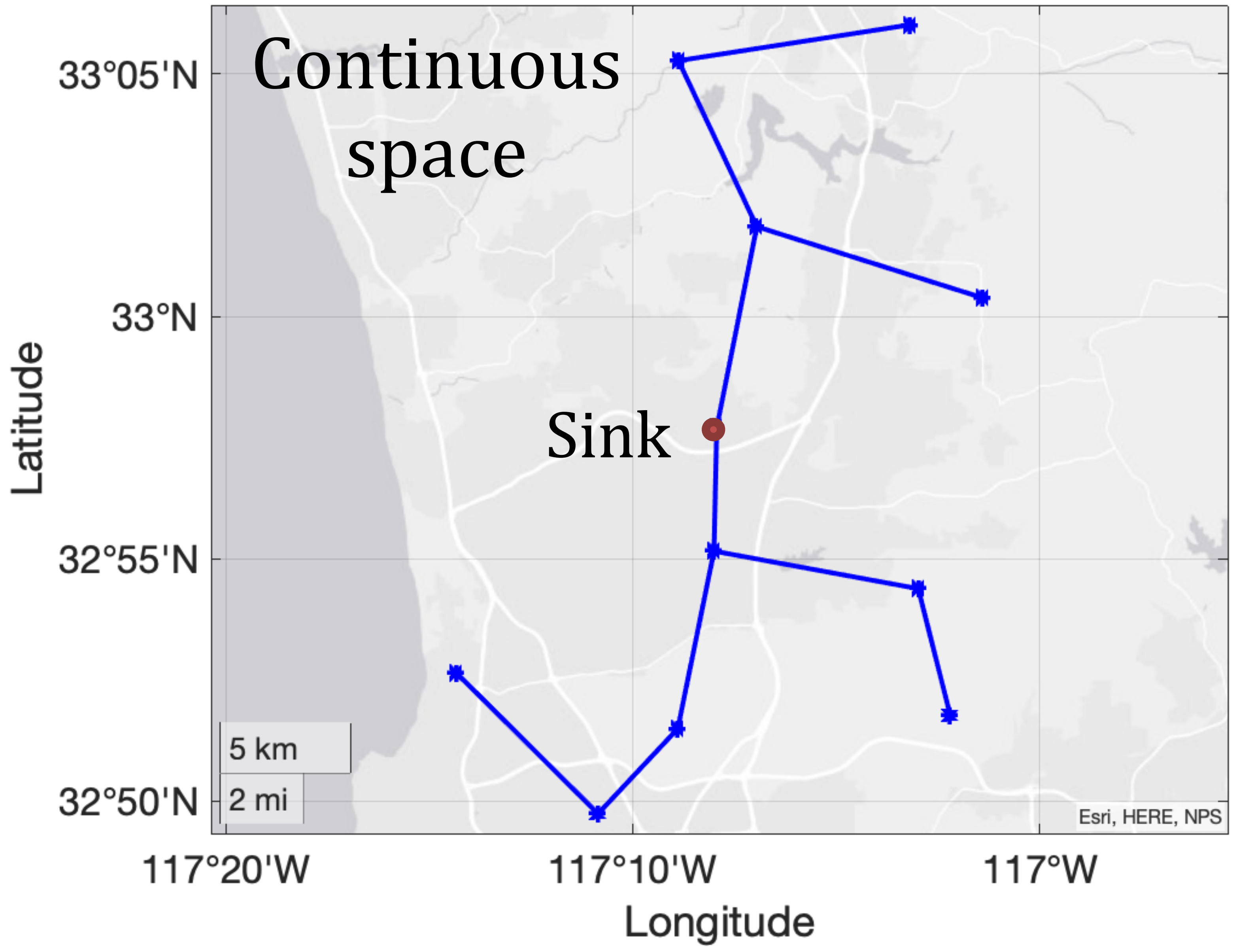


Our Contributions

- A formal model of maintenance cost for IoT networks
  - Focusing on permanent failures including electronics failures and battery depletion.

- A problem formulation for sensor deployment in a continuous space
  - Optimizing for the minimum maintenance cost
  - Under acceptable *sensing quality* and complete connectivity

- Application of two metaheuristics to efficiently approximate the optimal solution
  - Particle Swarm Optimization (PSO)
  - Artificial Bee Colony (ABC) optimization



Previous Works

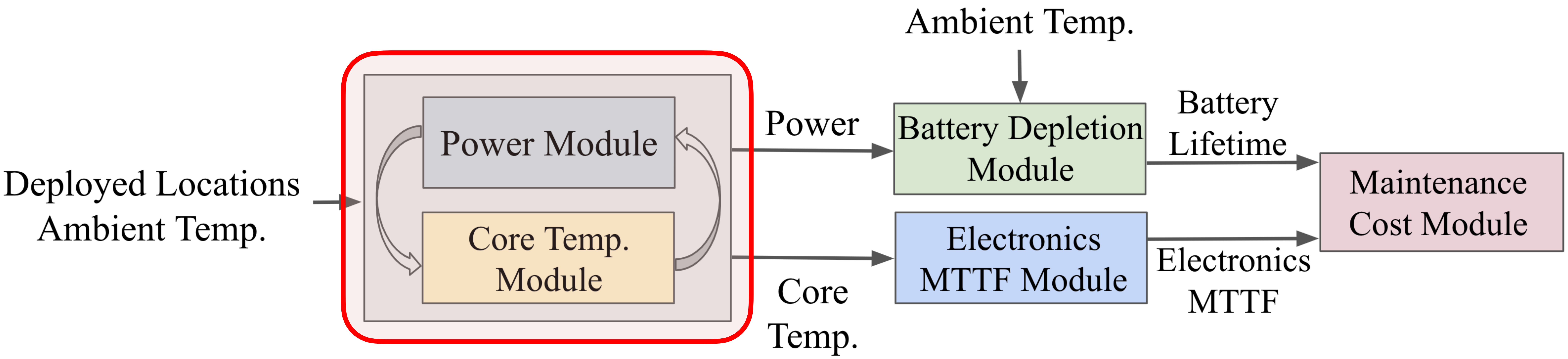
- Sensor deployment for environmental monitoring [Du 2015, Boubrima 2019]
  - Continuous reading (e.g. temperature) vs. target coverage
  - *Sensing quality* based on mutual information [Krause 2011]

(+) Justify the *sensing quality* definition
(+) Propose of a heuristic named **pSPIEL** and prove of its lower performance bound

(-) Use discrete candidate locations
(-) Assume noise-free sensors
(-) Fail to consider lifetime and reliability factors

- Reliability-oriented deployment in IoT 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 improves fault tolerance but does not reduce maintenance cost!

Maintenance Cost Model



- Power Module

$$P = P_{SoC}(T_c) + P_{comm} + P_{per}$$

→ Peripheral Power, e.g. sensor

↓ Static and Dynamic SoC Power

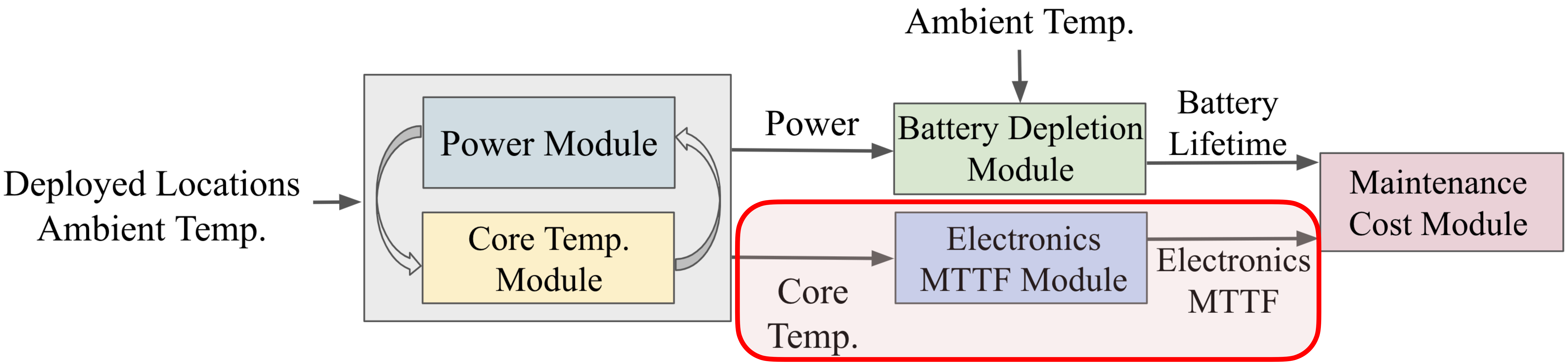
↘ Communication Power

- Core Temperature Module [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

Maintenance Cost Model (Cont.)



- Electronics Mean-time-to-failure (MTTF) models considering different failure mechanisms [Mercati 2016]:
  - Time-dependent dielectric breakdown (TDDB)
  - Negative bias temperature instability (NBTI)
  - Hot Carrier Injection (HCI)

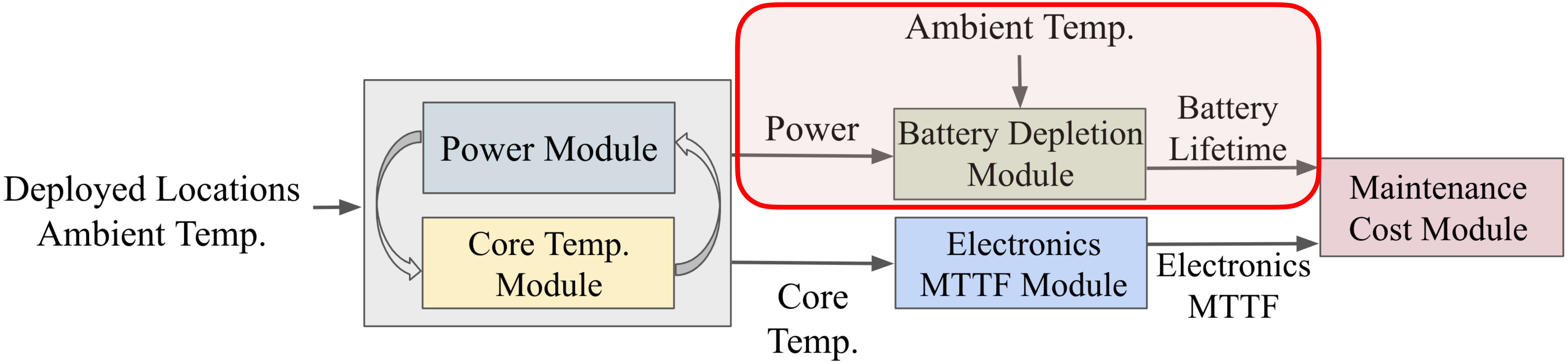
Exponential Temperature Factor!

Share a similar form with different constant c :

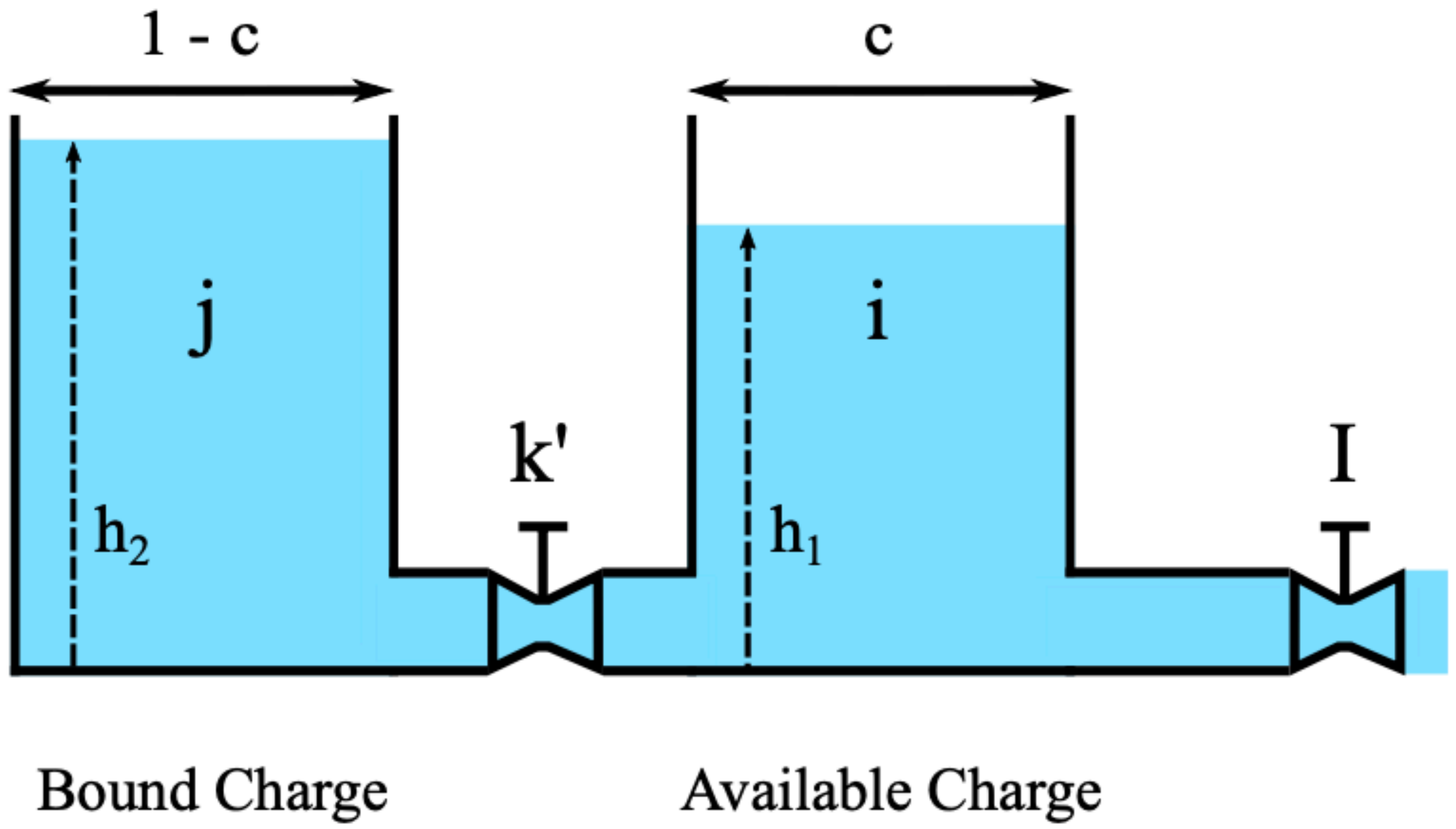
$$MTTF = c \exp\left(\frac{E_a}{kT_c}\right)$$

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

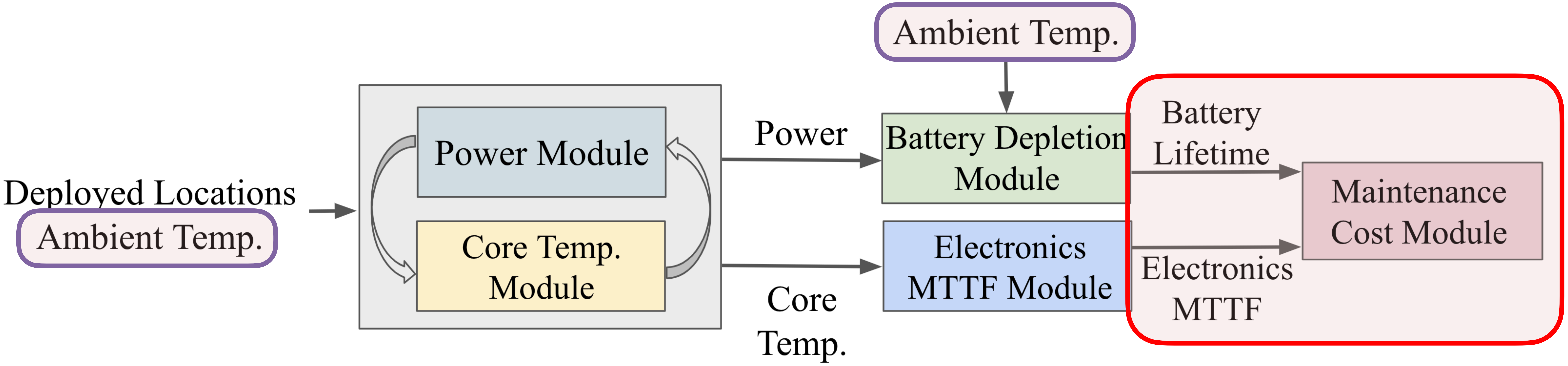
Maintenance Cost Model (Cont.)



- Temperature-Dependent Kinetic Battery Model (T-KiBaM) [Rodrigues 2017]
  - **Available charge**: supply the load directly
  - **Bound charge**: gradually refill the available charge
  - Refill rate depends on height difference and ambient temperature



Maintenance Cost Model (Cont.)



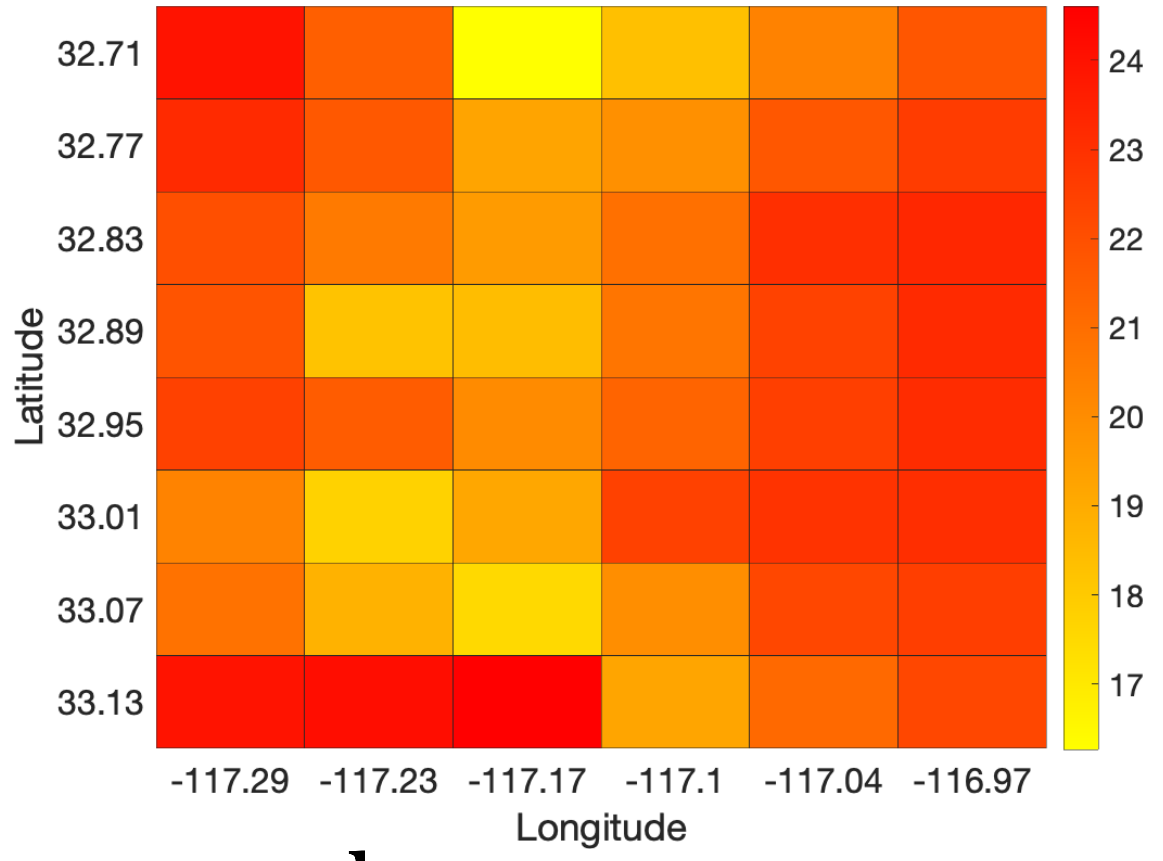
$$\text{Maintenance Cost} = \sum_{\text{All deployed devices}} \frac{\text{Cost}_{\text{battery}}}{\text{Battery Lifetime}} + \frac{\text{Cost}_{\text{device}}}{\text{Electronics MTTF}}$$

Battery Replacement Cost

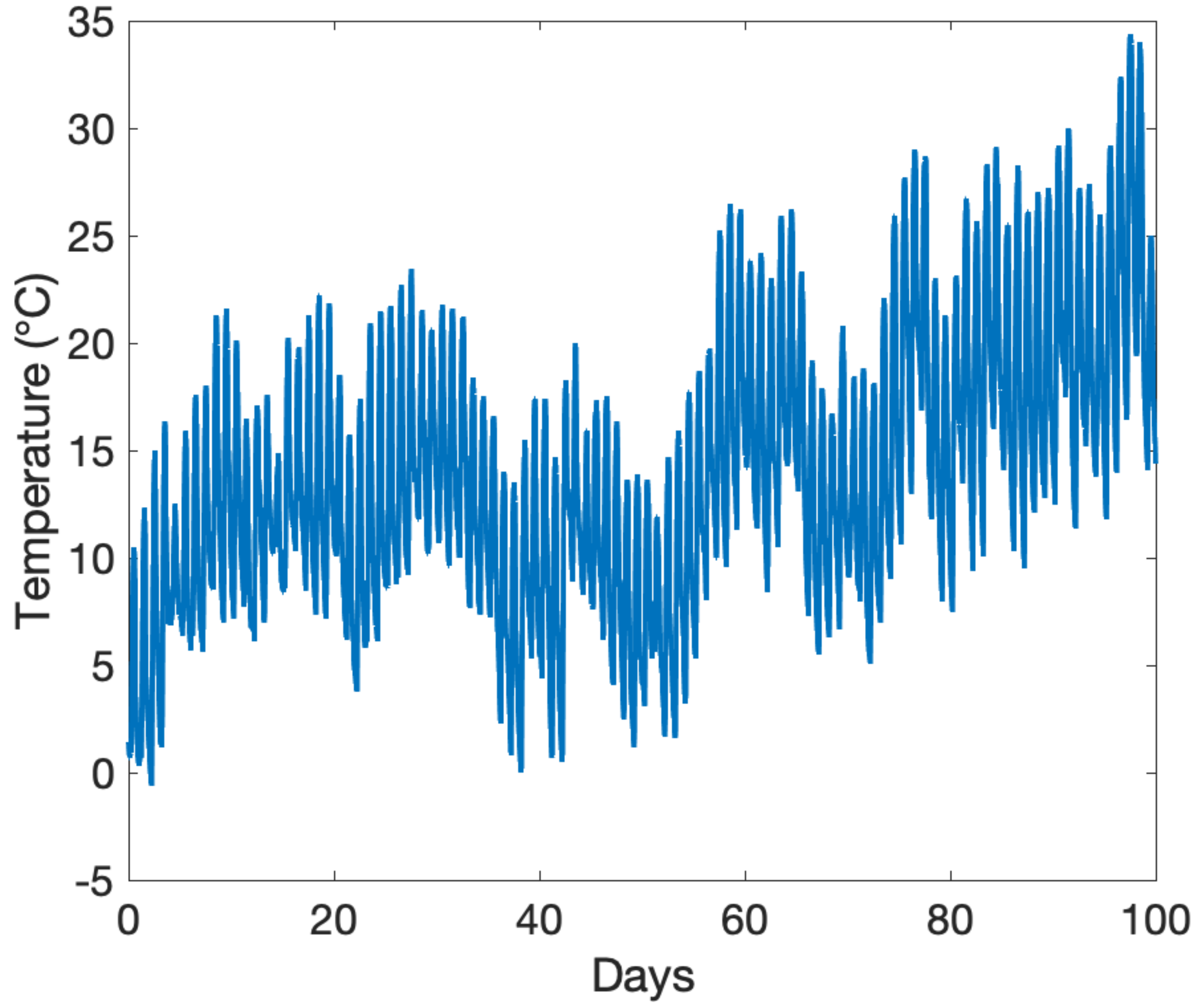
Device Replacement Cost

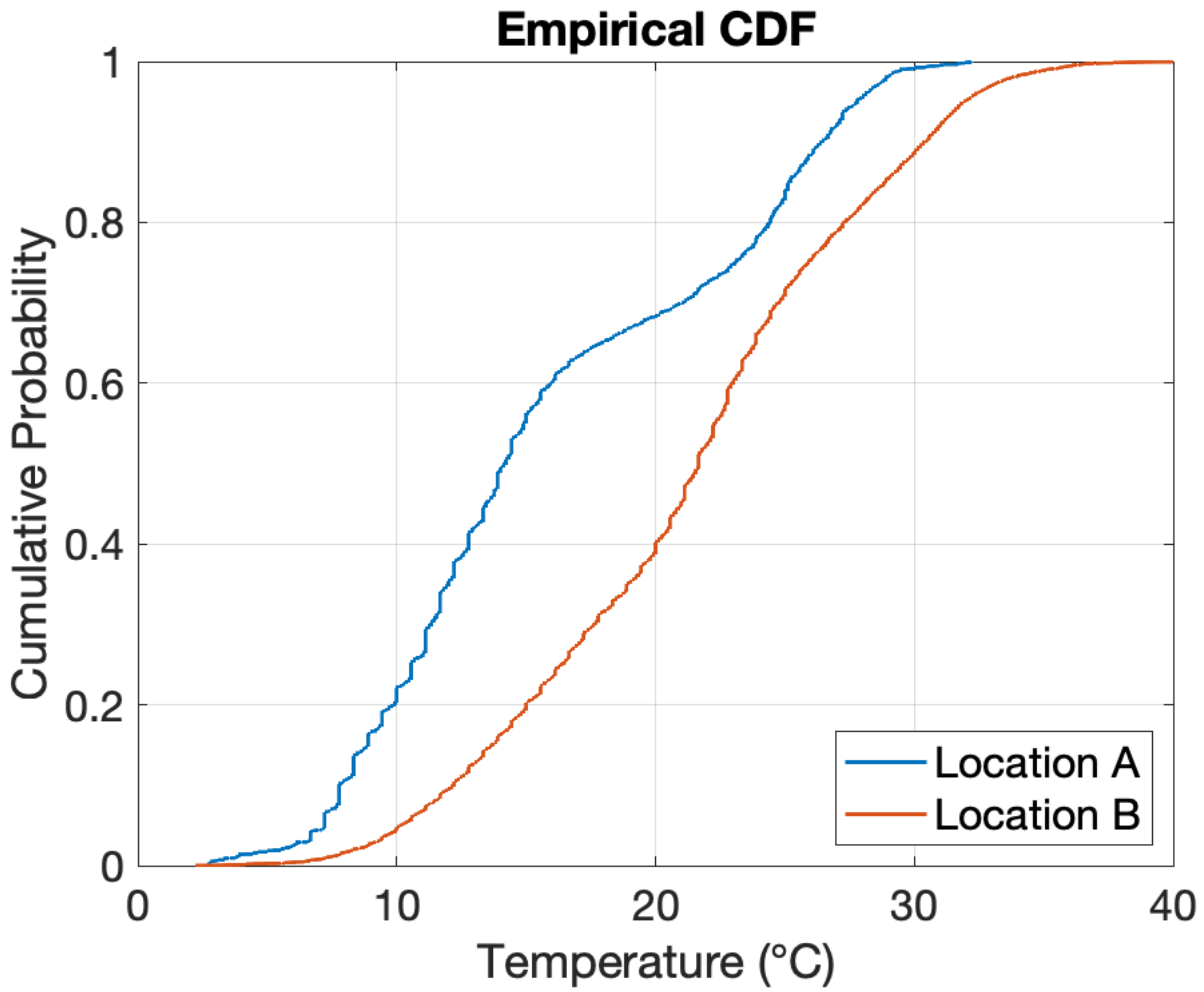
Maintenance Cost Under Temperature Variations Over Time

- Spatial temperature variation



- Temporal temperature variation





For this one node, maintenance cost at location B is 1.1x of the cost at location A.

Cumulative distribution of temperature over time

Our method:
Integral on temperature distribution over time to compute battery lifetime and MTTF

Sensing Quality [Krause 2011]

- A metric to evaluate the information gain in global distribution by placing finite sensors into a continuous space
- *Sensing Quality*

$$F(A) = \frac{H(X_V) - H(X_V \mid X_A)}{H(X_V)}, \quad 0 \leq F(A) \leq 1$$

- A : A set of deployed locations
- V : A set of undeployed locations
- X_V, X_A : Sensor readings at V and A
- $H(var)$: Entropy of variables var

- Examples
  - $F(A) = 1$ -> We can predict the readings at V with deployment A with 100% accuracy
  - $F(A) = 0.1$ -> We can reduce the uncertainty in predicting X_V by 10% compared to its original uncertainty

Problem Formulation

- How to deploy m sensors to minimize maintenance cost while satisfying
  - Acceptable sensing quality
  - Complete connectivity

$$\begin{aligned}
\min_{A} \quad & R_M(A) \\
\text{s.t.} \quad & F(A) \geq Q \\
& g_{pq} - \sum_{q \in \Gamma(p)} g_{qp} = R, \quad \forall p \in A \\
& \sum_{q \in \Gamma(c)} g_{qc} = mR, \quad \forall q \in A \\
& A \subset S, \quad |A| = m
\end{aligned}$$

Data Generation

Data Converge

Non-convex

Non-linear

Infinite Freedom

- Q : Predefined sensing quality threshold
- R : Generated data size of each sample
- $\Gamma(p) = \{q \in S \text{ where } d_{pq} < r\}$: Disc-like binary communication range
- S : A convex 2D deployable space

Metaheuristics

- Population-based metaheuristics employ a group of individuals to search in the high-dimensional space, ending up with sufficiently good solution.

- Fitness Function Design

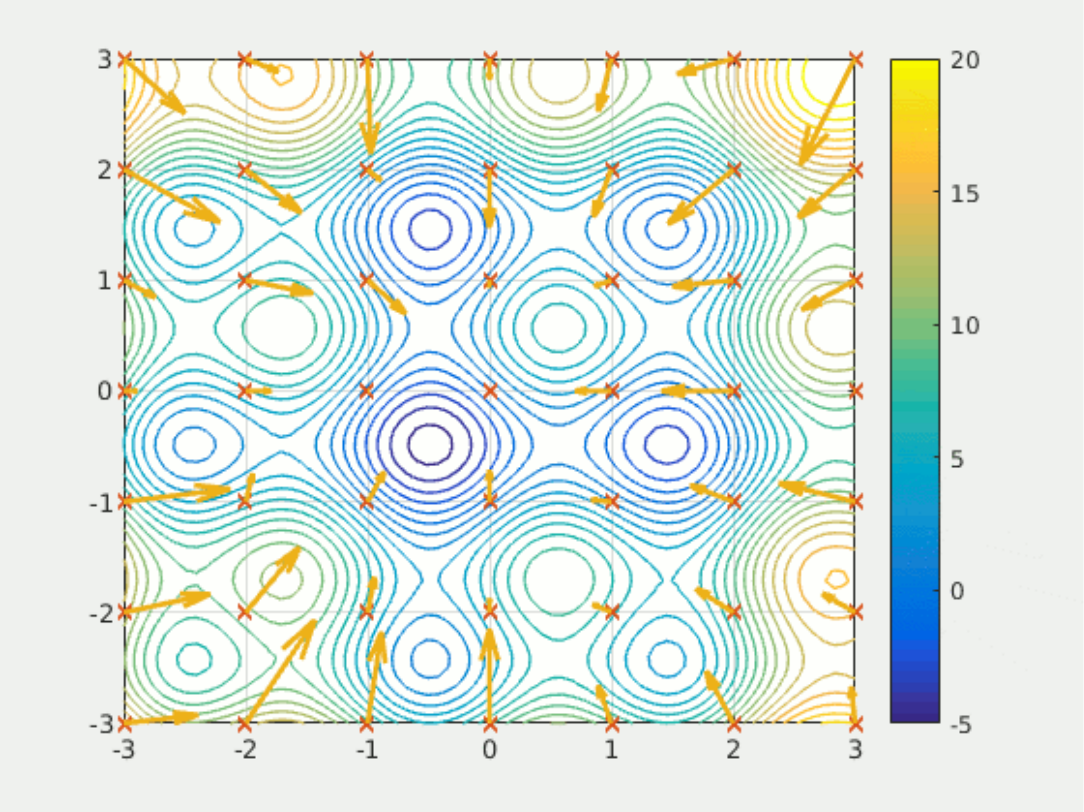
$$Fit(A) = w_1 R_M(A) + w_2 \max(Q - F(A), 0) + w_3 P_e \left|\text{unconnected nodes}\right|$$

Maintenance cost Benefit

Penalty for unsatisfied *Sensing Quality*

Penalty for incomplete connectivity

- Particle Swarm Optimization (PSO)
- Artificial Bee Colony (ABC) Optimization



Experimental Setup

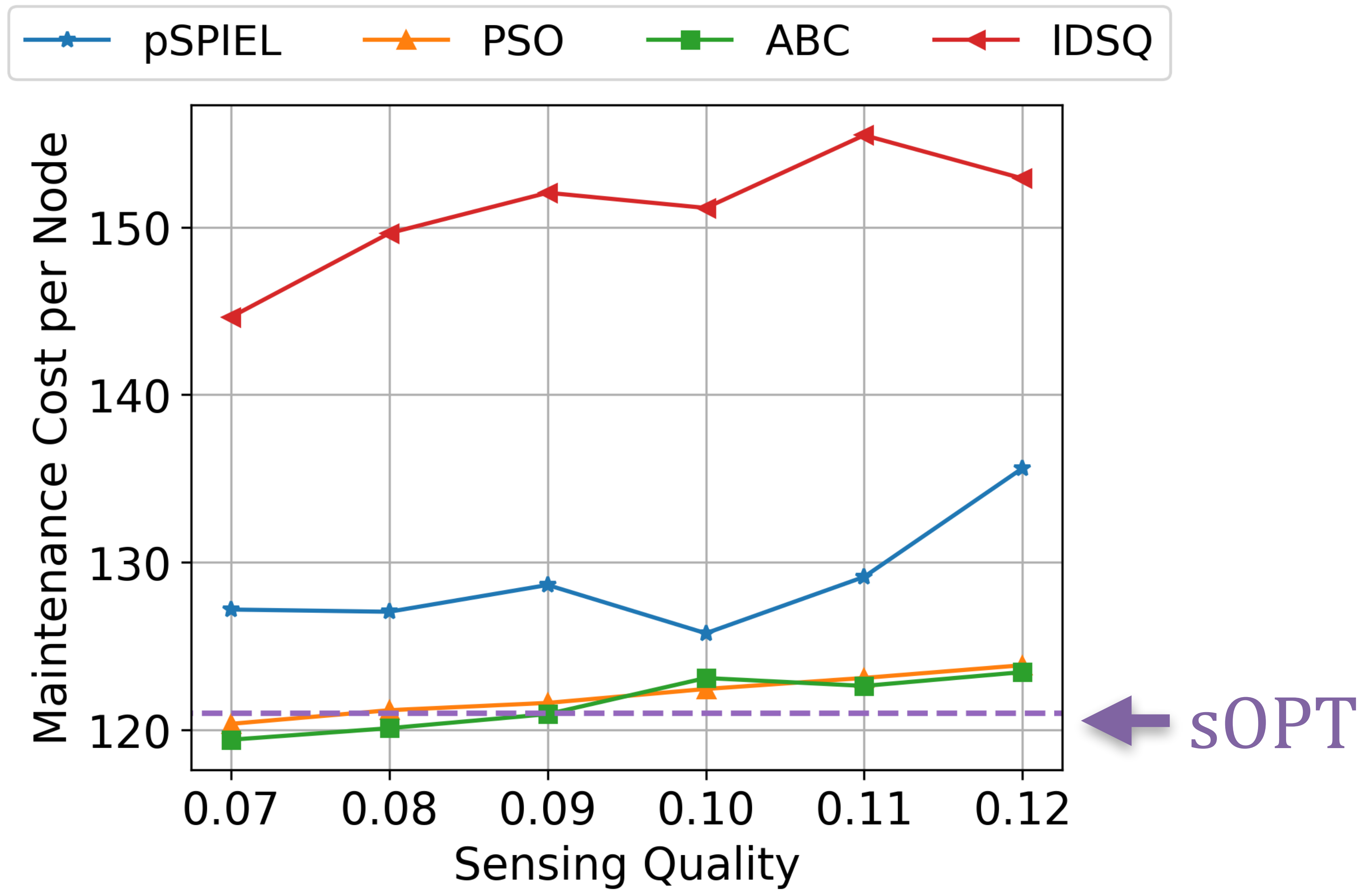
- We implement our maintenance cost model and sensor deployment approach in MATLAB R2020a[1].
- Simulations are performed on a Linux desktop with Intel Core i7-8700 CPU at 3.2 GHz and 16-GB RAM.
- We download environmental monitoring history from PurpleAir[2] as predeployment data
  - Both datasets are in Southern California with temperature, humidity, air quality metrics (i.e., pm1, pm2.5, pm10) samples every 10 minutes.
  - Small-region: 30 km × 50 km, from Jan. 1, 2019 to Feb. 20, 2020.
  - Large-region: 60 km × 100 km, from Jan. 1, 2019 to Apr. 1, 2020.
- Baselines
  - **IDSQ** [Zhao 2004]: greedy heuristic
  - **pSPIEL** [Krause 2011]: clustering and greedy selection in each cluster
  - **sOPT:** a relaxed version of the original optimization problem

} Discrete candidate locations

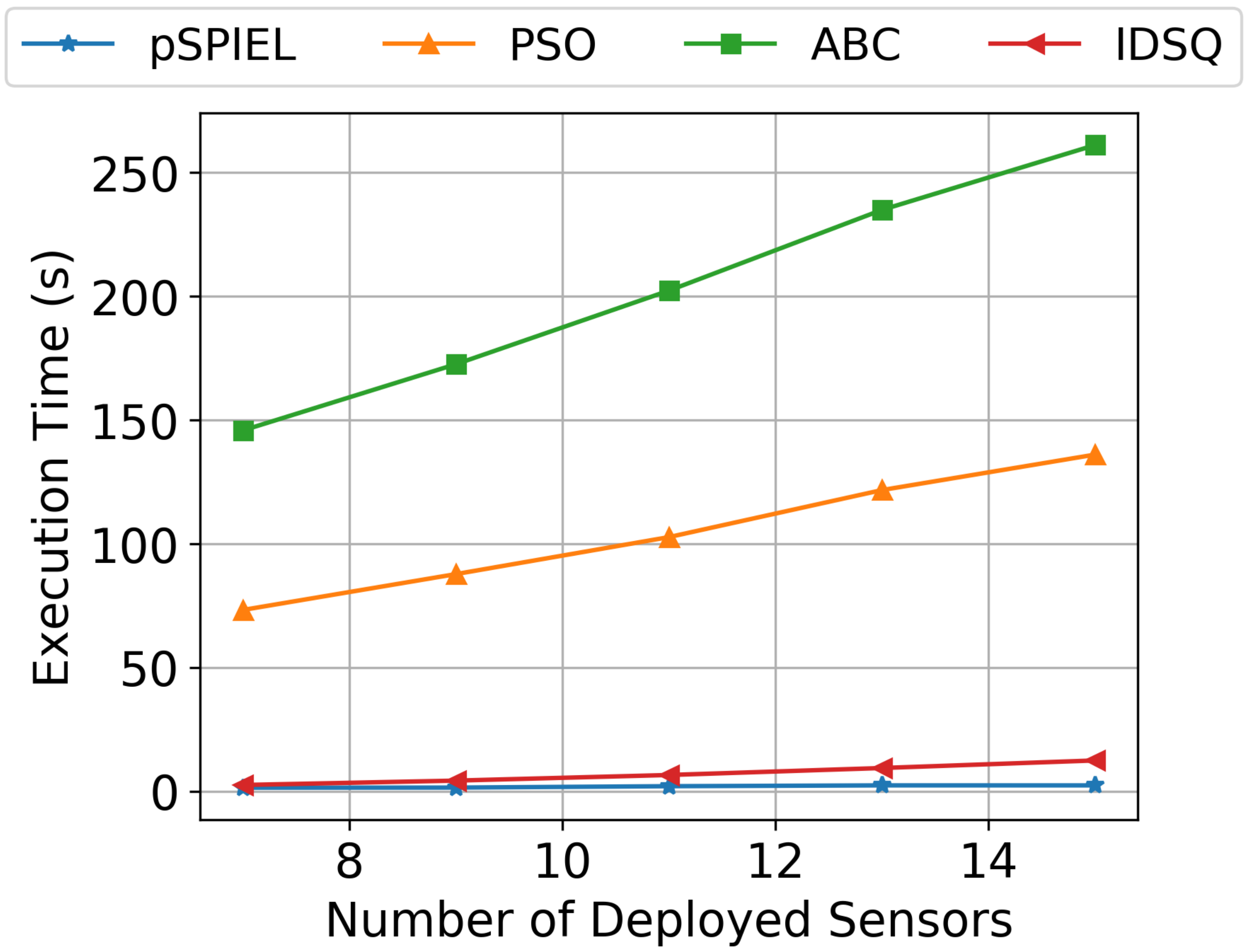
1. Source code is available at https://github.com/Orienfish/AQI-deploy.
2. PurpleAir, https://www2.purpleair.com/.

Simulation Results on the Small Region

Trade-off between *Sensing Quality* and Maintenance Cost



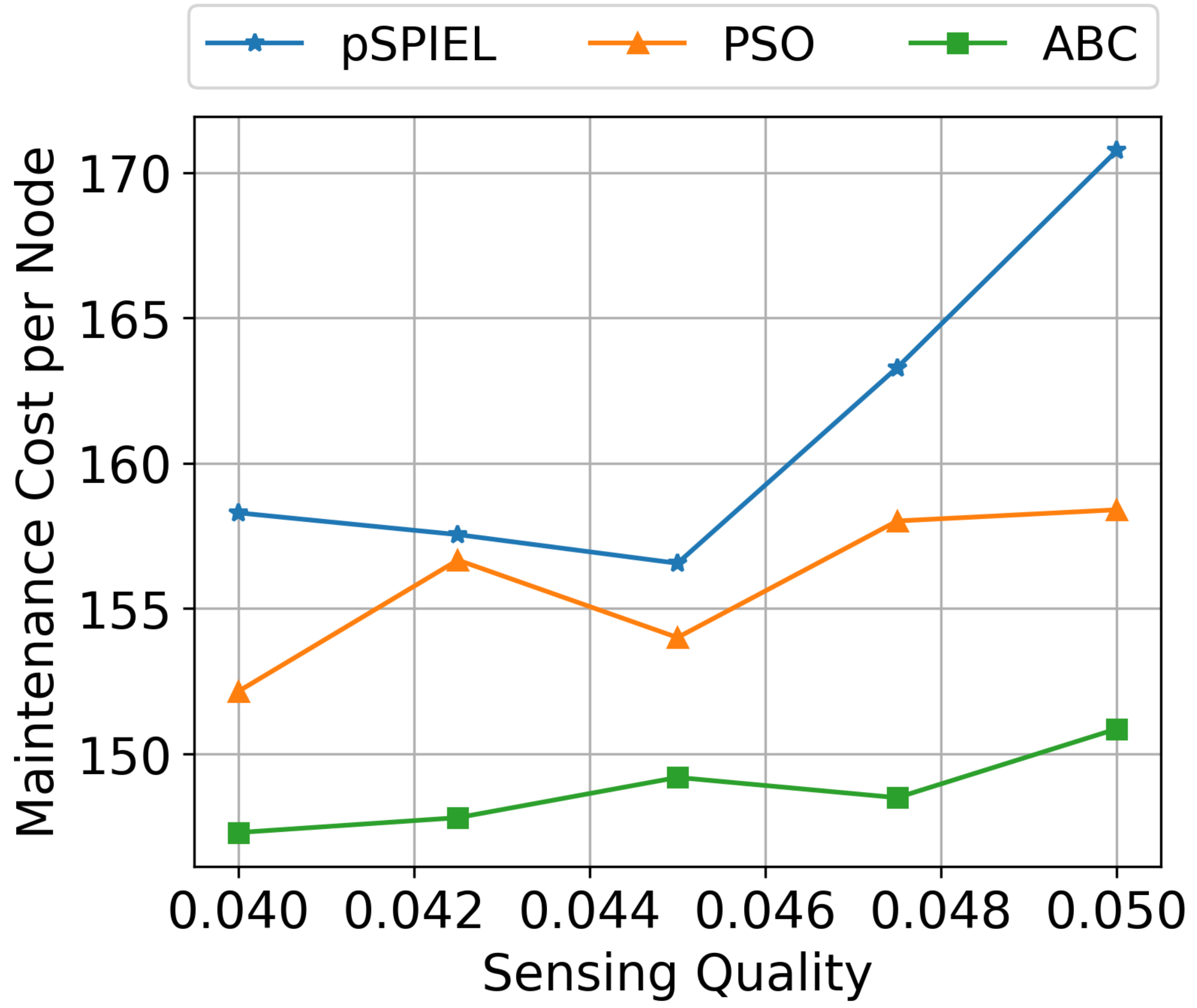
Execution Time



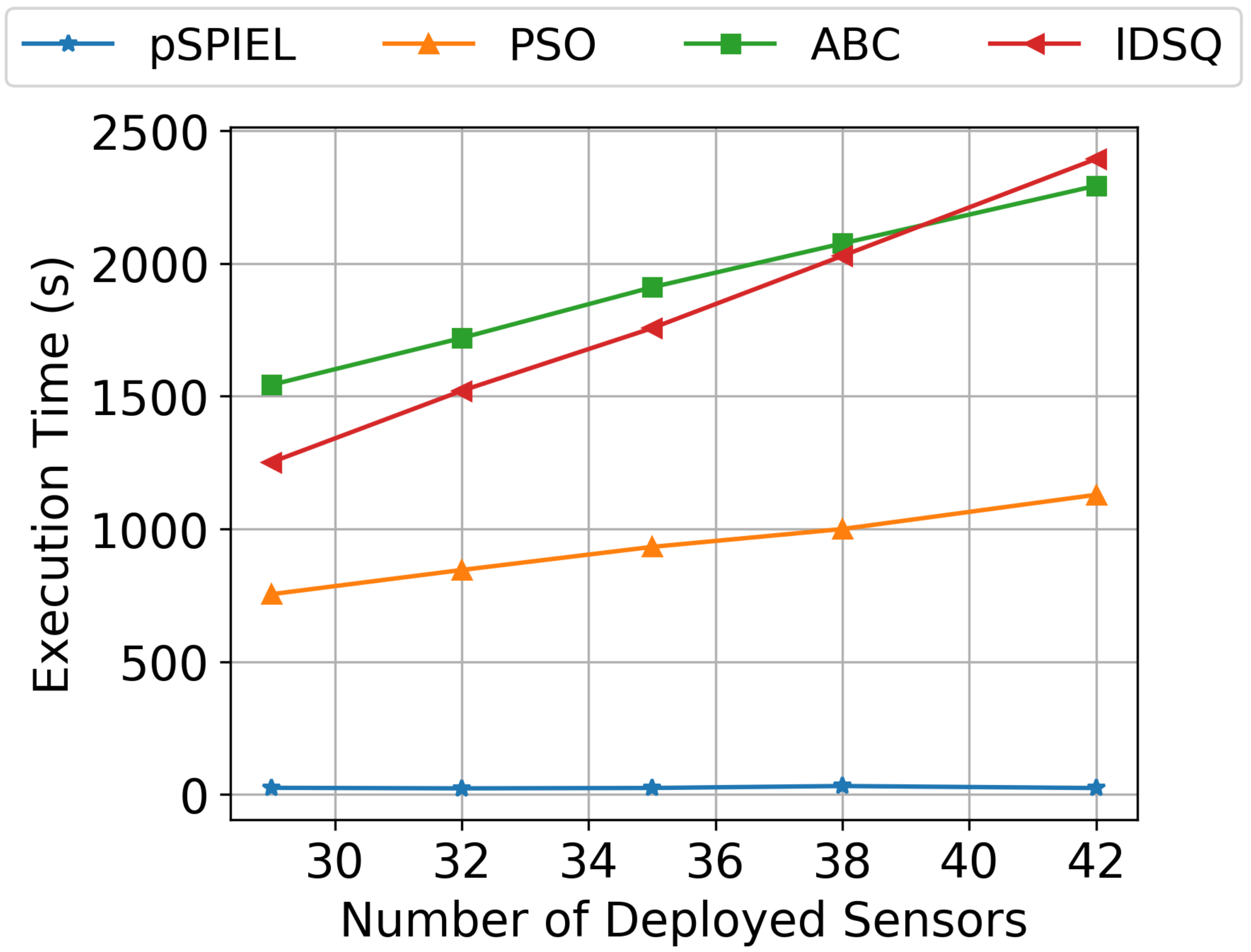
- Our heuristics save maintenance cost of 19% and 20% respectively compared to existing greedy algorithm
- Our heuristics achieve or even surpass the relaxed boundary given by sOPT
- ABC takes 2x longer than PSO due to extra searching trials in each iteration

Simulation Results on the Large Region

Trade-off between *Sensing Quality* and Maintenance Cost



Execution Time



- Our heuristics save maintenance cost up to 40% compared with existing greedy algorithm, at the cost of longer execution time
- Our heuristics extend the minimum battery depletion time and electronics MTTF by 2.69x and 2.8x respectively

Conclusion

- We develop a novel maintenance cost model for IoT networks
  - Our model focuses on permanent failures, i.e., battery depletion and electronics failures, incorporating the exponential temperature factor
- We formulate a sensor deployment problem optimizing for minimum maintenance cost while satisfying acceptable *Sensing Quality* and complete connectivity
- We apply two metaheuristics, i.e., PSO and ABC, to approximate the optimal solution
- Large-scale simulation results show that our approach saves up to 40% of average maintenance cost compared to existing greedy algorithm

Thanks!

Questions?

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