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COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

# Panda: Neighbor Discovery on a Power Harvesting Budget

**Robert Margolies**, Guy Grebla, Tingjun Chen,
Dan Rubenstein, Gil Zussman

# The Internet of Tags

- Small energetically self-reliant tags
- Enabling technologies
  - Energy harvesting with lightweight components
  - Low power wireless communications
  - Energy adaptive algorithms

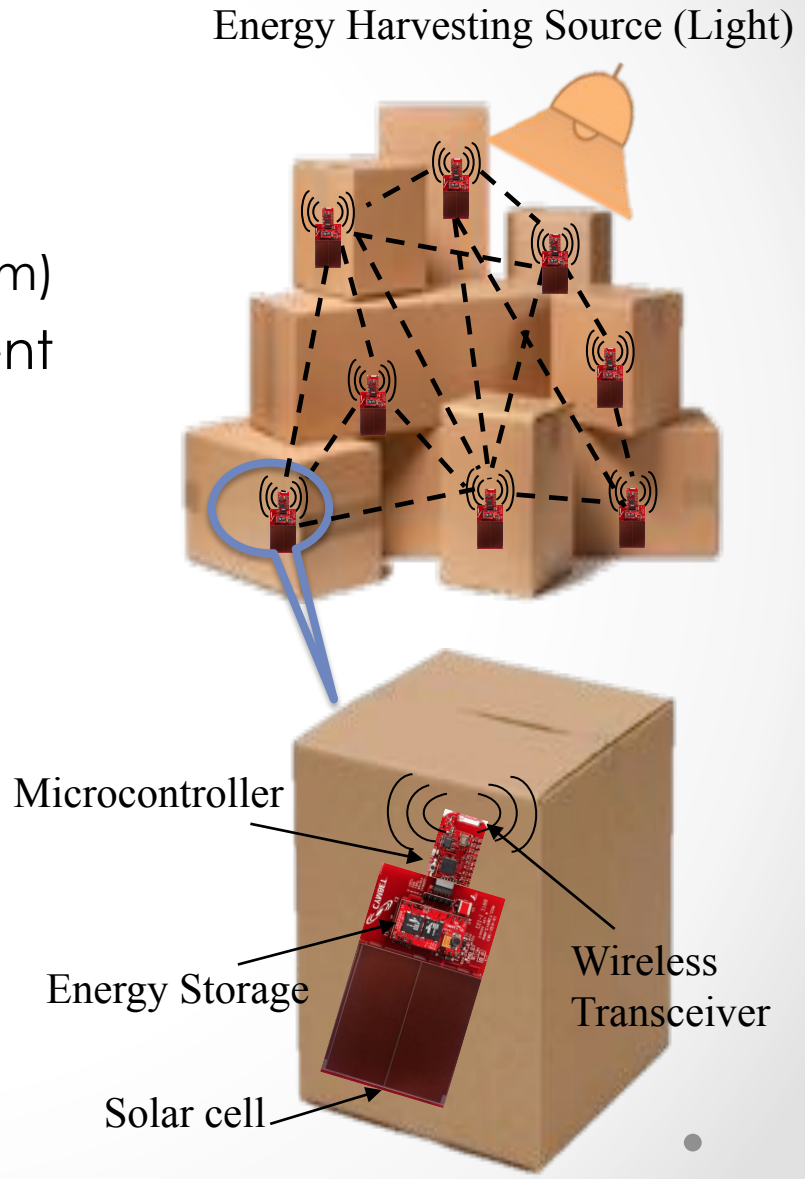
Smart Buildings

Monitoring of Objects

Searching Objects:
Where are my keys?

# An Example Application
## Locating misplaced boxes in a warehouse

- Boxes equipped with small tags
  - Harvest light energy
  - Communicate within short range
  - Exchange IDs (Dewey Decimal System)
- A box whose ID is significantly different from its neighbors is identified (e.g., flashing an LED)
- Related Works
  - Margolies et. al. "Energy-harvesting active networked tags (EnHANTs)". ACM. Trans. Sens. Netw. 2015.
  - Liu et. al. "Ambient backscatter: wireless communication out of thin air" Proc. ACM SIGCOMM. 2013.
  - Wang, Katabi. "Dude, where's my card? RFID positioning . . ." Proc. ACM SIGCOMM. 2013.



# Panda: A Neighbor Discovery Protocol

- Neighbor discovery is key to searching and monitoring applications
- Perpetual neighbor monitoring – last forever
- Extremely limited energy budget: tags can only be active for small periods of time
- Achieving and maintaining coordination is difficult

We design, analyze, and experimentally evaluate the Panda protocol, which maximizes the rate of neighbor discovery under a power budget

# Outline

- Introduction and Motivation
- Prototype Description
- Model and Objective
- Panda Protocol
  - Description
  - Analysis and Optimization
  - Panda-Dynamic
- Experimental Evaluations
- Conclusions

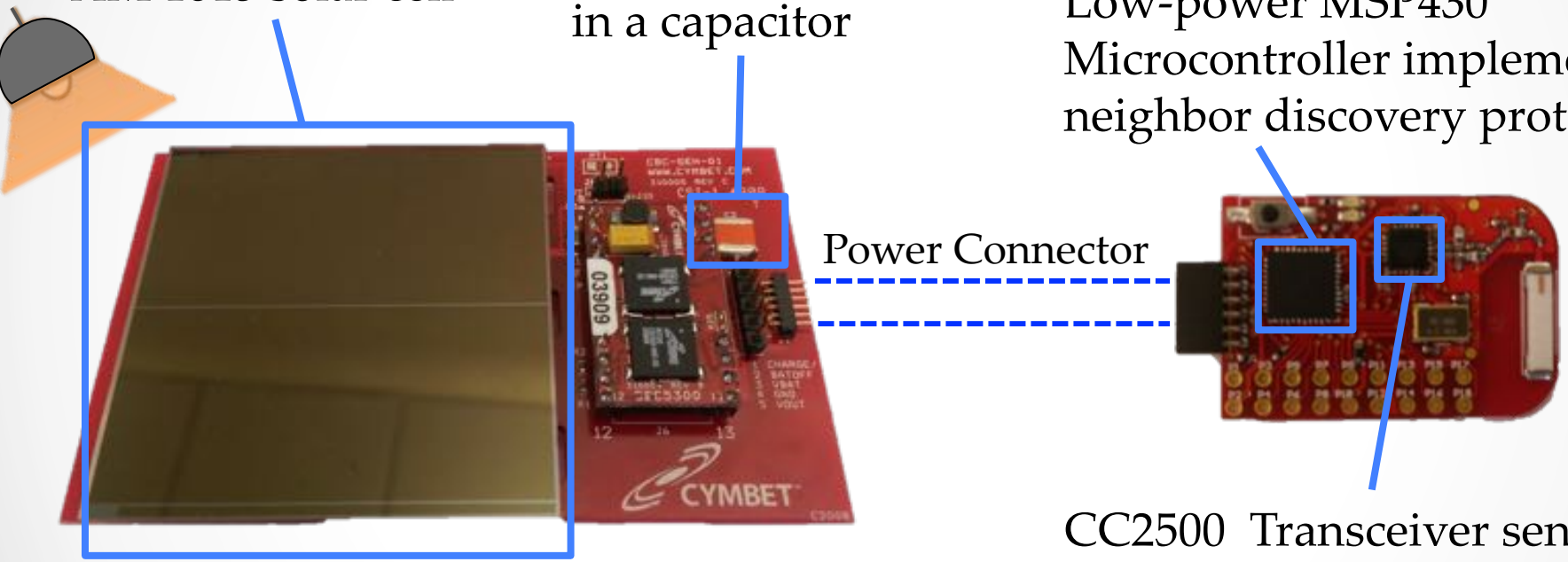
# Prototype Description

- Prototype based on the TI eZ430-RF2500-SEH

Powered by Sanyo AM 1815 solar cell

Energy stored in a capacitor

Low-power MSP430 Microcontroller implements neighbor discovery protocol

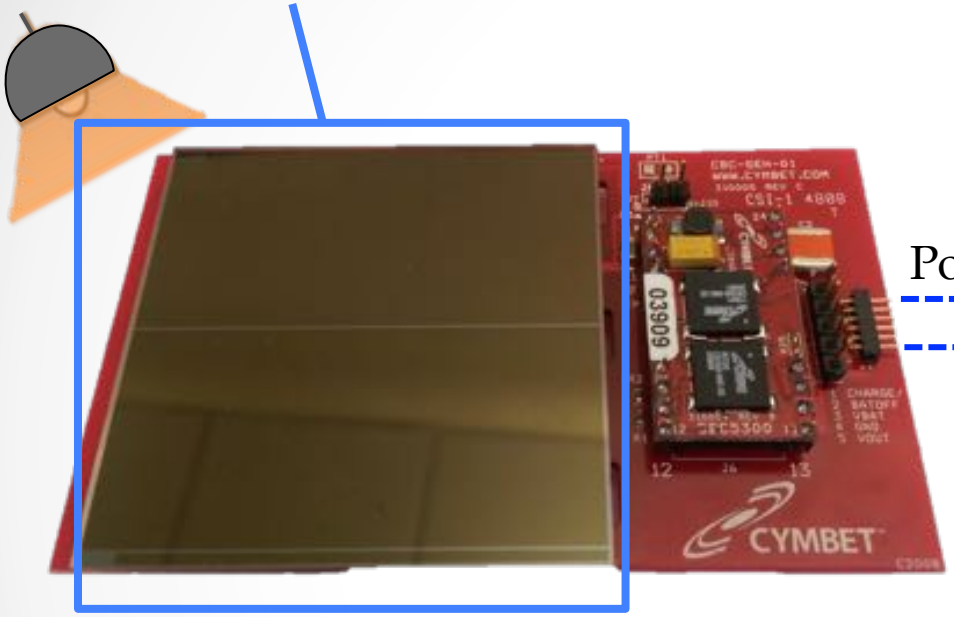



CC2500 Transceiver sends neighbor discovery messages

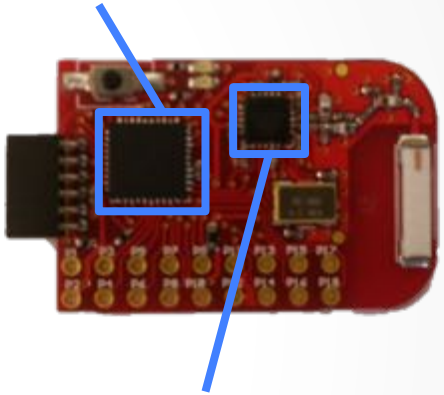
- R. Margolies, M. Gorlatova, J. Sarik, G. Stanje, J. Zhu, P. Miller, M. Szczodrak, B. Vigraham, L. Carloni, P. Kinget, I. Kymissis, G. Zussman, "Energy Harvesting Active Networked Tags (EnHANTs): Prototyping and Experimentation," ACM Transactions on Sensor Networks, vol. 11, no. 4, pp. 62:1-62.27, Nov. 2015.

# Model

Powered harvested at average rate of $P_b$ (mW)




Power Connector



Neighbor discovery protocol to exchange ID messages of length $M$ (ms)

CC2500 Transceiver can be in 3 states:

- Sleeping ($P_s \approx 0$ mW )
- Listen ( $P_r$ mW)
- Transmit ($P_t$ mW )

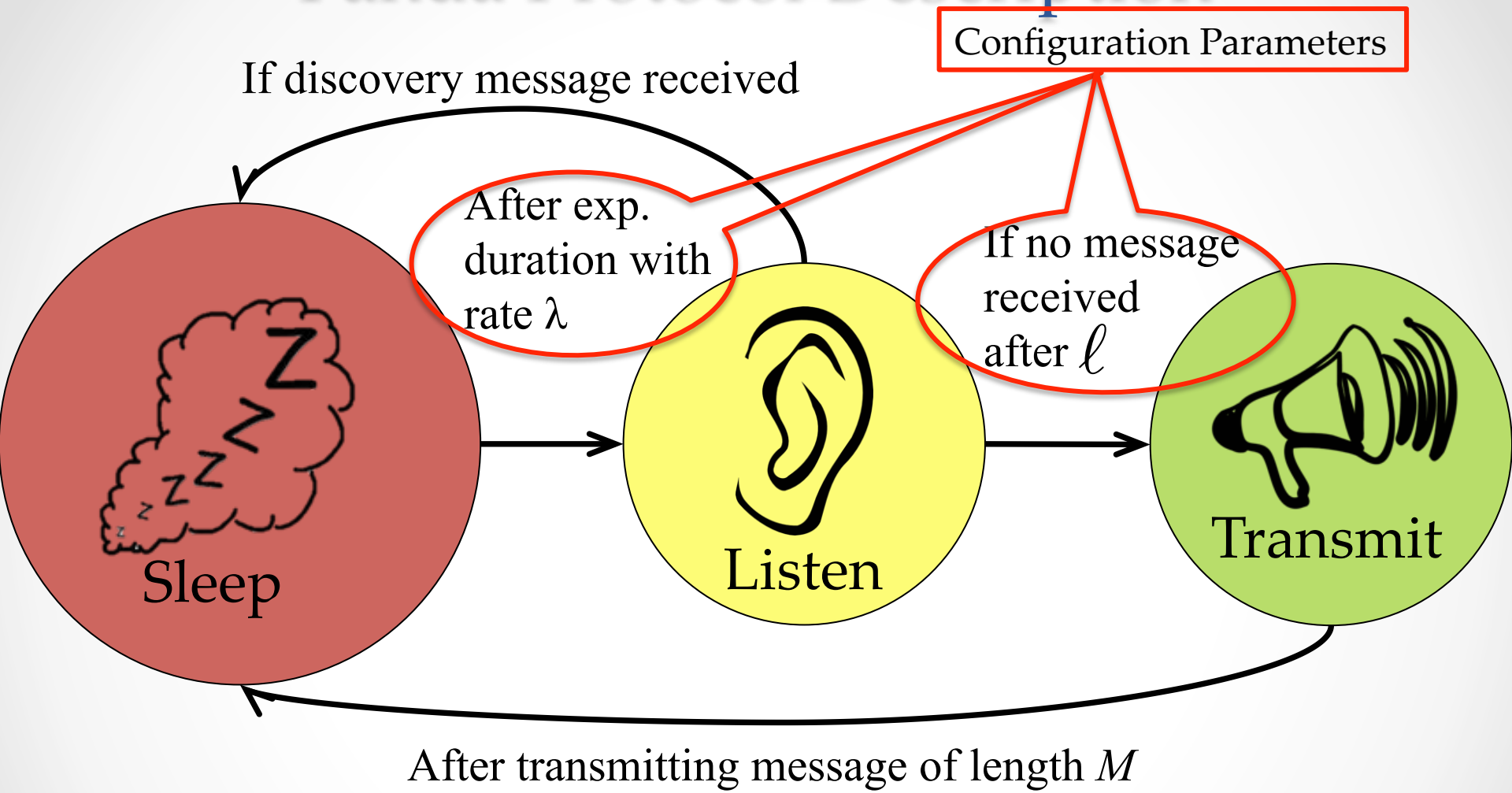
Objective: Maximize the neighbor discovery rate, while maintaining energy neutrality

# Model and Related Work

- Our Goal: Develop a protocol that maximizes the rate of **neighbor discovery**
- Subject to **energy neutrality:** power consumed matches power harvested
- Related work
  - Attempts to minimize the worst-case discovery latency
  - Duty cycle constraint, instead of a power budget
  - Does not incorporate radio power consumption
  - Probabilistic Protocol: Birthday
  - Deterministic Protocol: Searchlight


- M. Bakht, M. Trower, and R. H. Kravets, "Searchlight: Won't you be my neighbor?" in *Proc. ACM MobiCom'12*, Aug. 2012.
- M. J. McGlynn and S. A. Borbash, "Birthday protocols for low energy deployment and flexible neighbor discovery in ad hoc wireless networks," *in Proc. of ACM MobiHoc'01*, Oct. 2001.

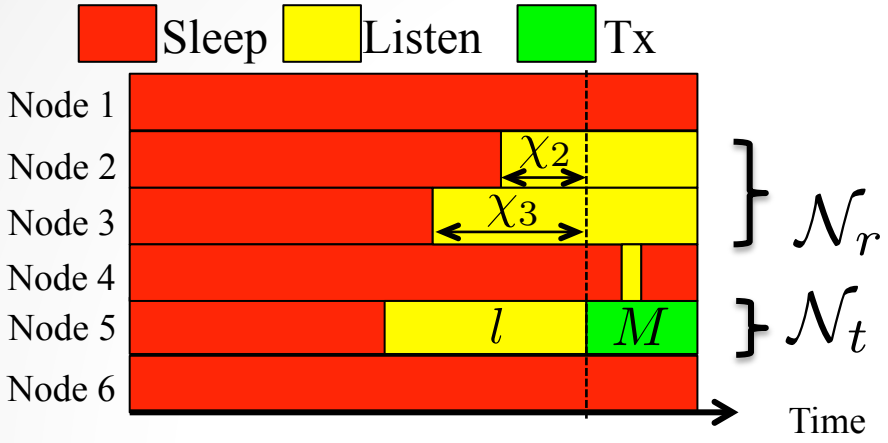
# Panda Protocol Description



# Panda Protocol: Configuration

- Goal: Select the exponential sleep rate, $\lambda$ , and listen duration, $\ell$, to maximize discovery Rate, $U$.
- Panda: designed for environments with homogenous nodes
  - $N$ nodes arranged in a clique topology (no packet errors)
  - All nodes are homogenous with a power budget of $P_b$
  - The number of nodes, $N$, is known a-priori
- Panda Dynamic (Panda-D)

# Panda Protocol: Discovery Rate



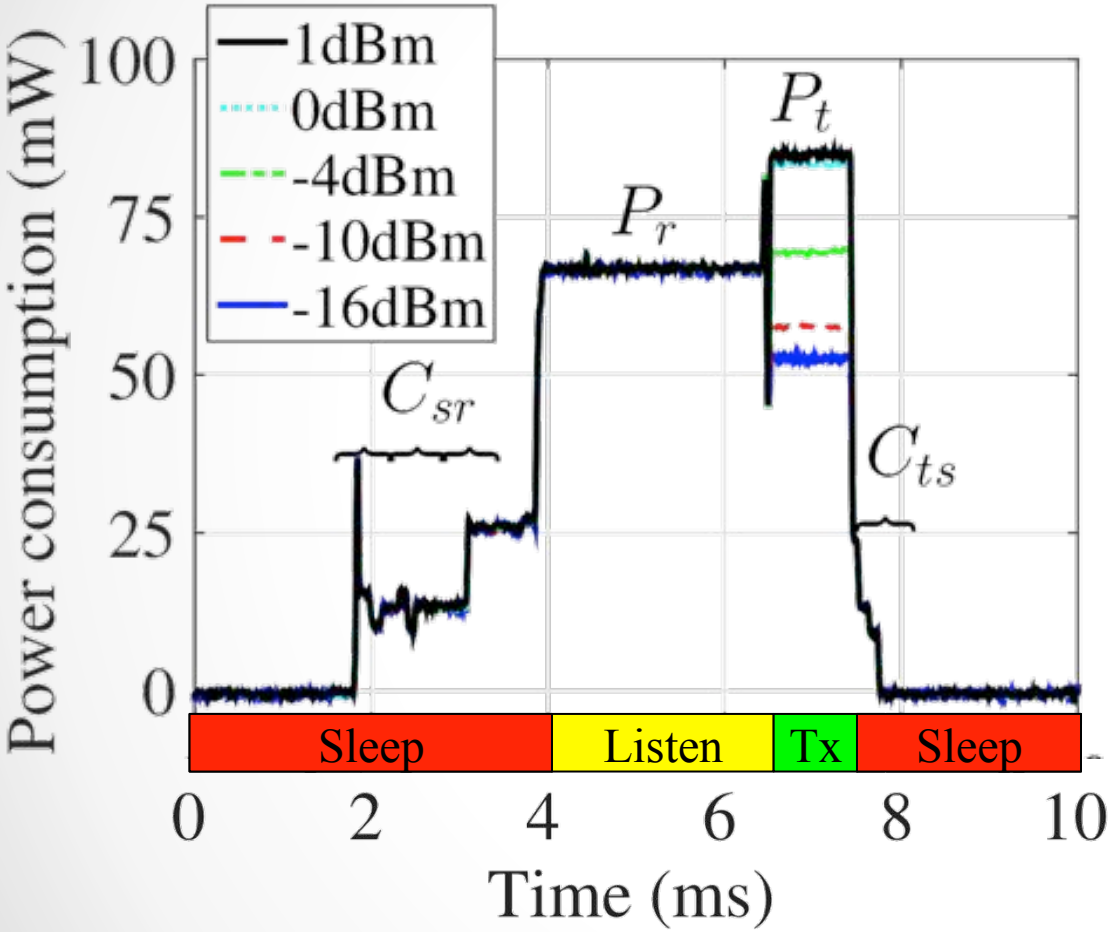

Expected Renewal Duration, $\rho$

$$\frac{1}{N\lambda} + l + M$$

- Discovery Rate ($U$) =

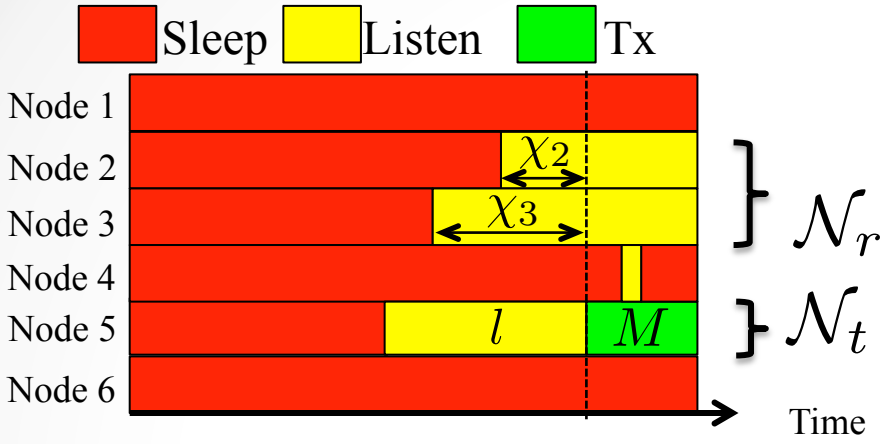
$$\frac{\text{Expected Number of Discoveries}}{\text{Expected Length of Renewal}} = \frac{E[|\mathcal{N}_r|]}{\rho} = \frac{(N-1)(1-\mathrm{e}^{-\lambda l})}{\frac{1}{N\lambda} + l + M}$$

# Panda Protocol: Power Consumption




| Parameter | Cost |
|---|---|
| $P_t$(mW) | 59.23 |
| $P_r$(mW) | 64.85 |
| $M$(ms) | 0.92 |
| $C_{sr}(\mu$J) | 74.36 |
| $C_{rs}(\mu$J) | 13.48 |
| $C_{ts}(\mu$J) | 4.83 |

# Panda Protocol: Power Consumption




Expected Renewal Duration, $\rho$

$$\frac{1}{N\lambda} + \ell + M$$

- Expected power consumption for a node in $\mathcal{N}_t$

$$\frac{1}{\rho}\Pr(n \in \mathcal{N}_t)(\text{Energy to listen for } l \text{ and transmit for } M)$$

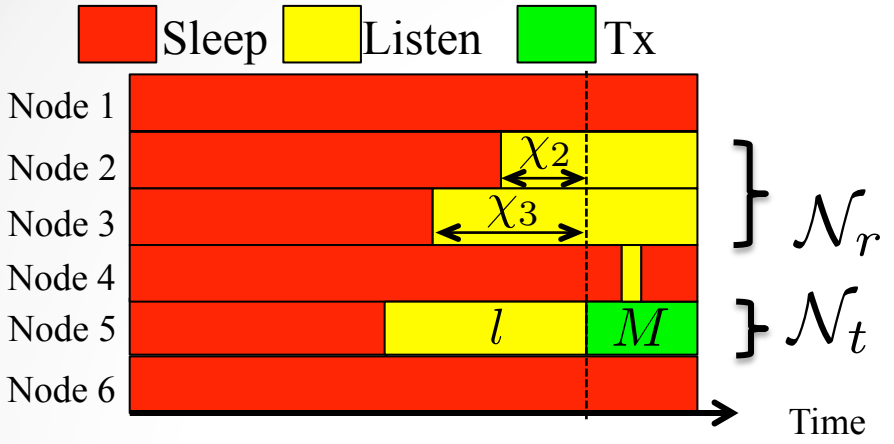
- Expected power consumption for a node in $\mathcal{N}_r$

$$\frac{1}{\rho}\Pr(n \in \mathcal{N}_r)(\text{Energy to listen for } \chi + M)$$

- Expected power consumption for all other nodes

$$\frac{1}{\rho}\Pr(n \notin N_t \cup N_r) \cdot 0 = 0$$

# Panda Protocol: Power Consumption




Expected Renewal Duration, $\rho$

$$\frac{1}{N\lambda} + \ell + M$$

- Expected power consumption for a node

$$\Phi = \frac{1}{\rho}\Pr(n \in \mathcal{N}_t)(\text{Energy to listen for } l \text{ and transmit for } M) + \frac{1}{\rho}\Pr(n \in \mathcal{N}_r)(\text{Energy to listen for } \chi + M) + \frac{1}{\rho}\Pr(n \notin N_t \cup N_r) \cdot 0 = 0$$

# Panda Protocol: Configuration

- Select the exponential sleep rate, $\lambda$ , and listen duration, $\ell$ , to maximize discovery Rate, $U$ ,

$$\max_{\lambda,l} \quad U = \frac{(N-1)(1-\mathrm{e}^{-\lambda l})}{\frac{1}{N\lambda} + l + M}$$

$$\text{s.t.} \quad \Phi \leq P_b$$

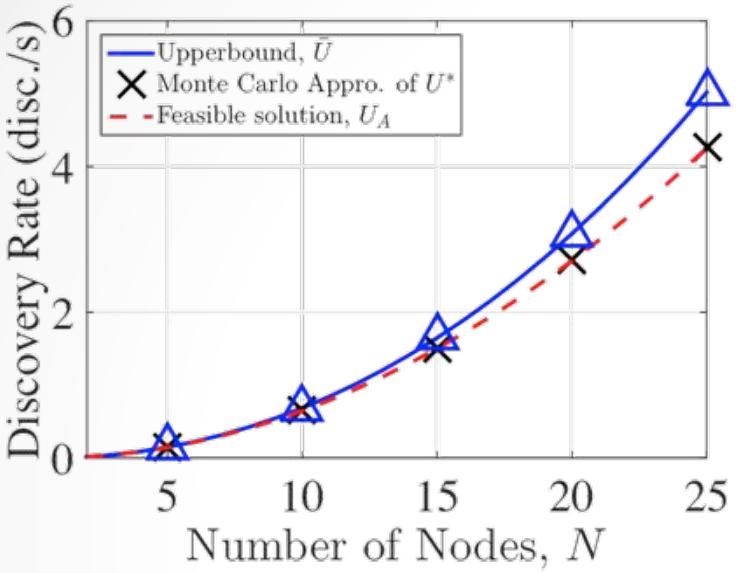
Non-convex

$$\text{where} \quad \Phi = \frac{\frac{1}{N}(C_{sr} + P_r l + P_t M + C_{ts}) + \frac{N-1}{N}(1-\mathrm{e}^{-\lambda l})(C_{sr} + P_r(\frac{1}{\lambda} - l\frac{\mathrm{e}^{-\lambda l}}{1-\mathrm{e}^{-\lambda l}} + M) + C_{rs})}{\frac{1}{N\lambda} + l + M}$$

- Numerical approximation solution $U_A$
- Derive an analytical upperbound $\overline{U*}$ using the approximation:

$$\mathrm{e}^{-x} \geq 1 - x \text{ for } x \geq 0, \text{ and } \mathrm{e}^{-x} \approx 1 - x \text{ for } x \approx 0.$$

# Panda Protocol: Configuration




Panda is numerically shown to achieve 94+% of the optimal discovery rate, while *obeying energy neutrality*

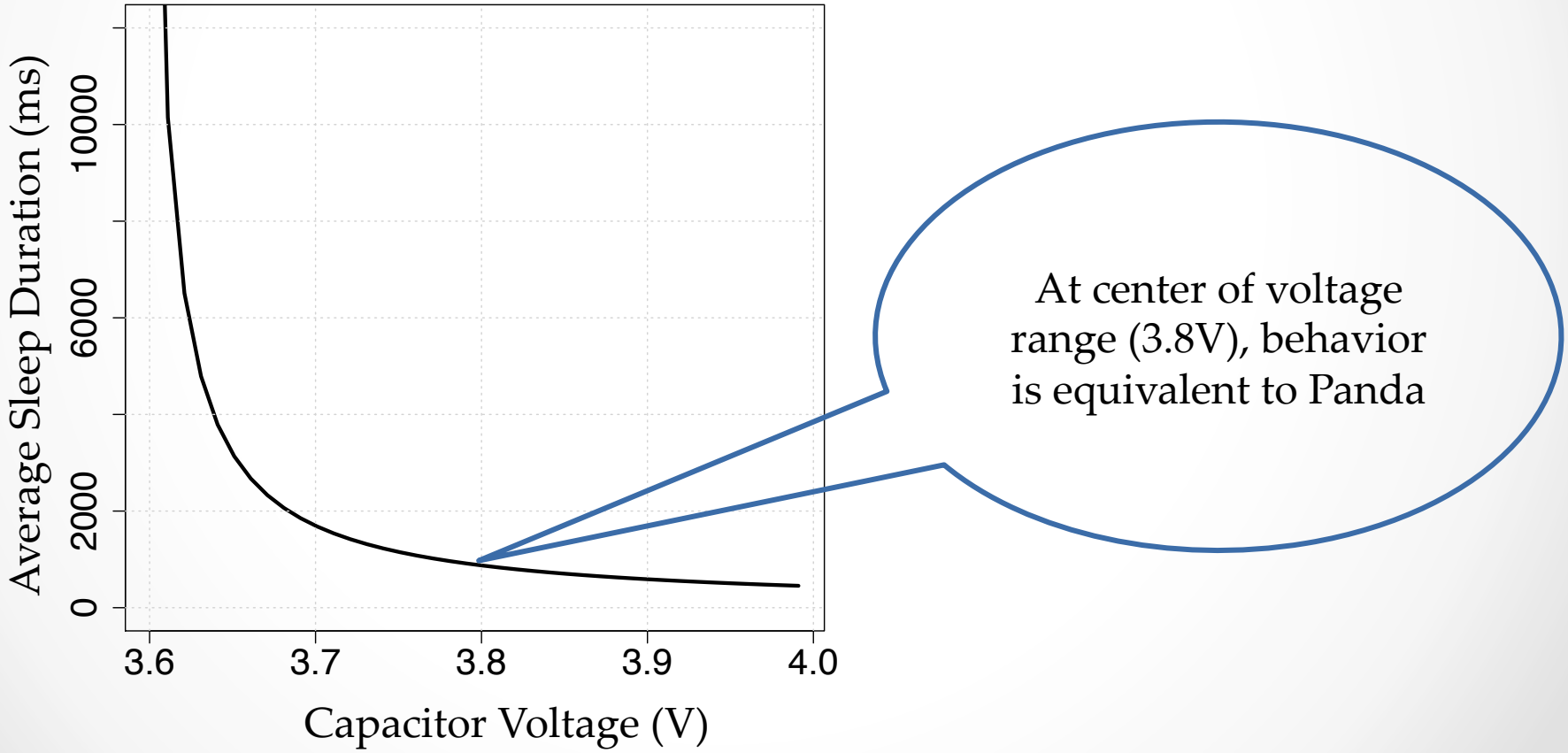
Where $U_A \leq U^* \leq \overline{U^*}$

- Numerical approximation solution $U_A$
- Derive an analytical upperbound, $\overline{U^*}$, using the approximation:

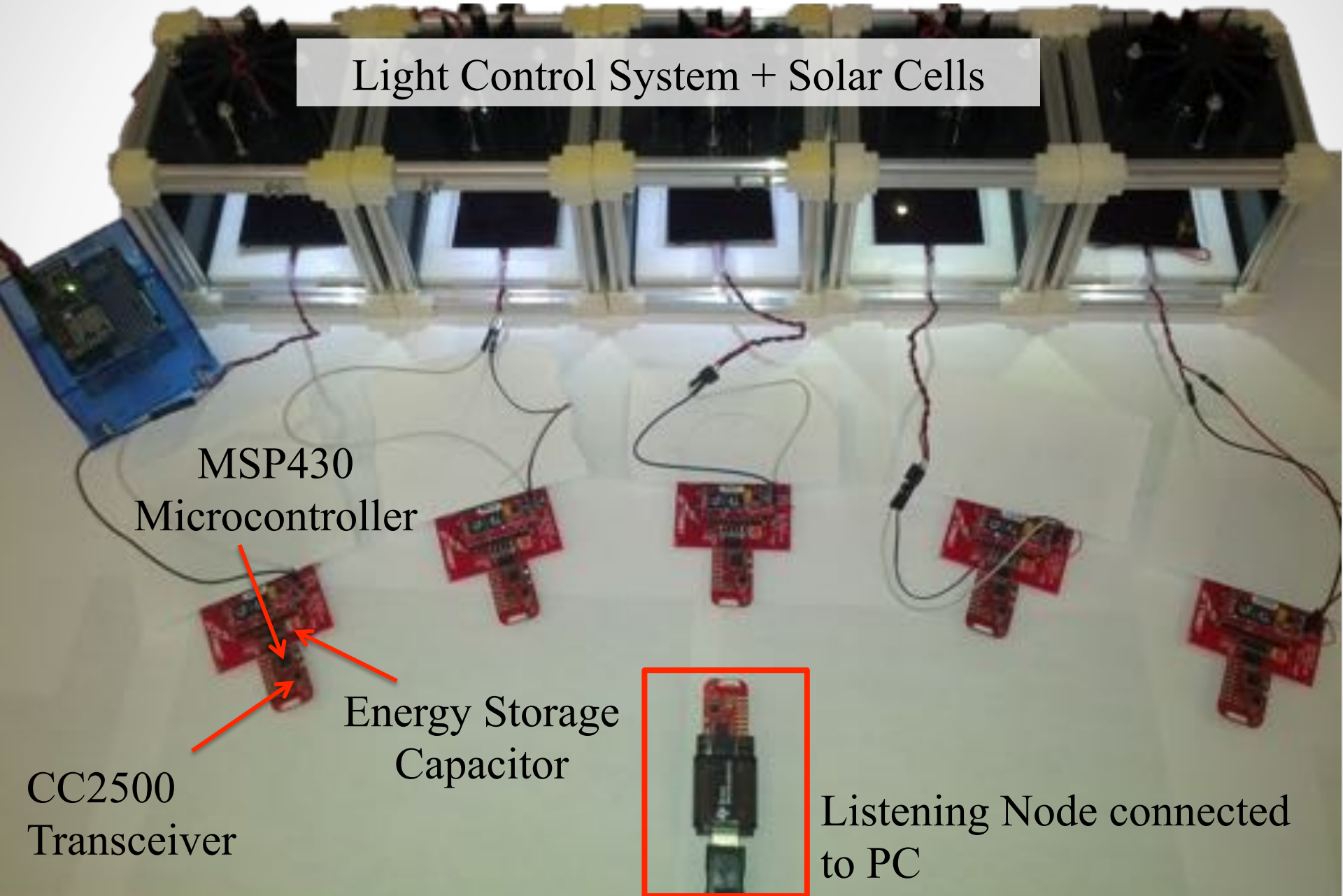
$$e^{-x} \geq 1 - x \text{ for } x \geq 0, \text{ and } e^{-x} \approx 1 - x \text{ for } x \approx 0.$$

# Panda - Dynamic

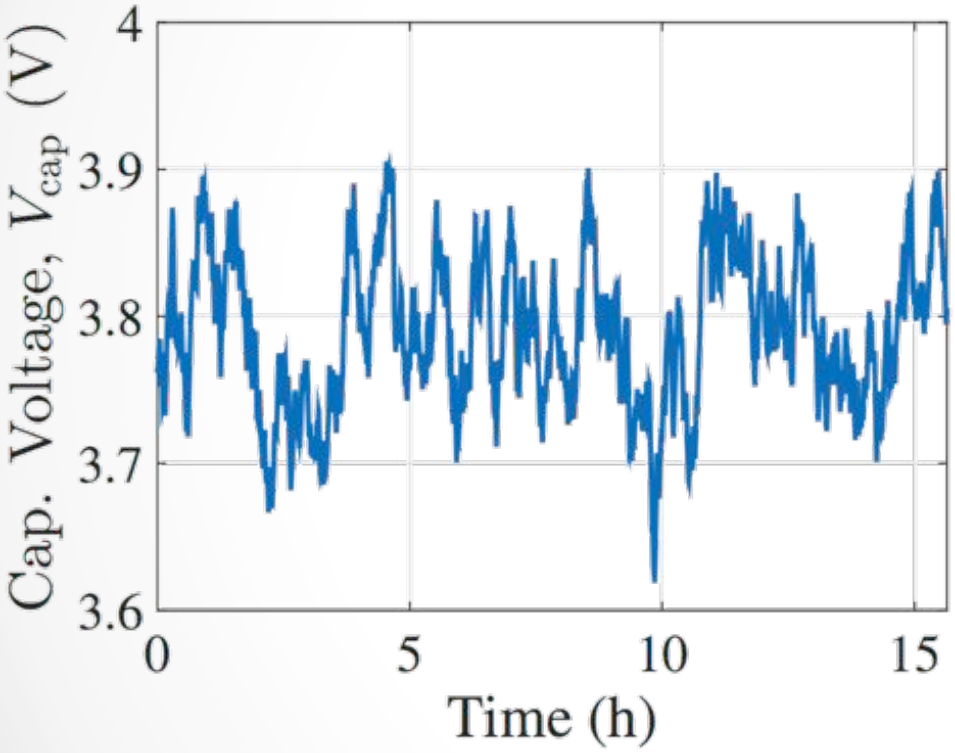
- Relax the homogeneity assumptions
- Adjust the node sleep duration based on power harvesting feedback from the capacitor voltage



# Experimental Performance Evaluation: Setup

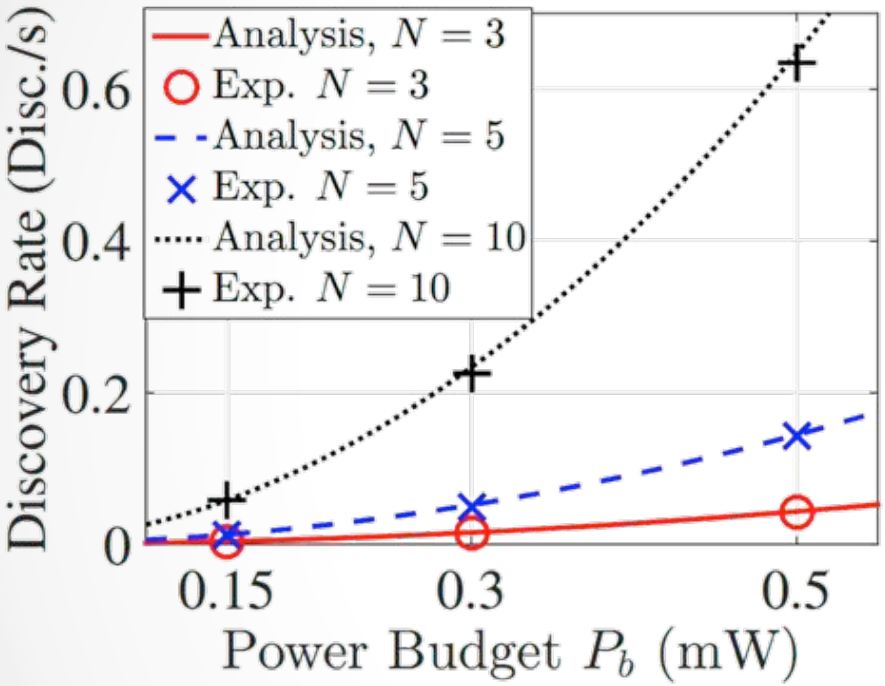


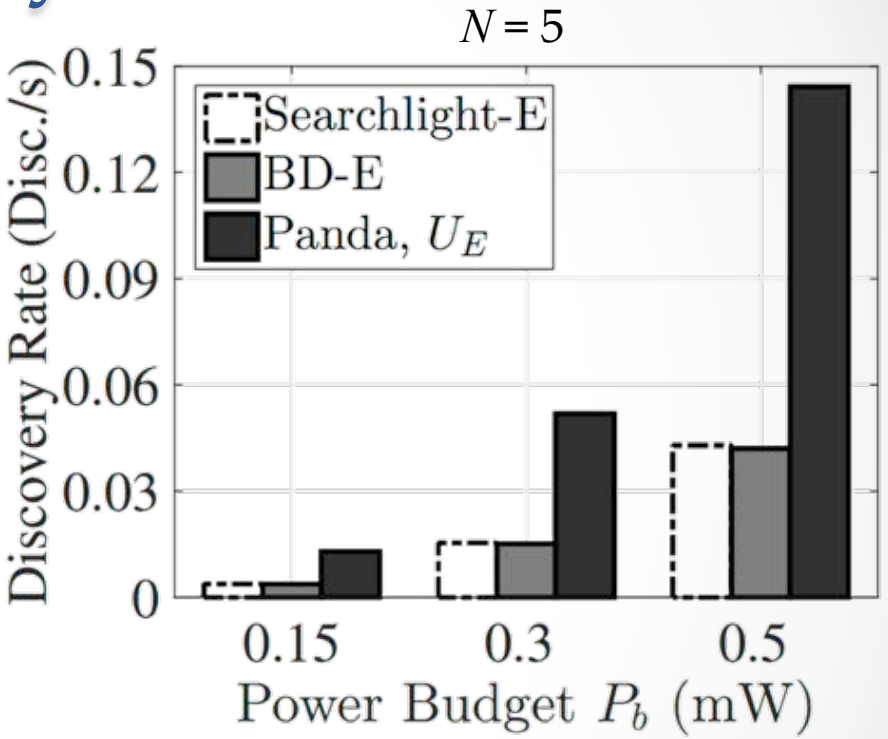
# Experimental Performance Evaluation: Power Consumption




Energy neutrality is demonstrated by the oscillation within the limits of the storage of the capacitor

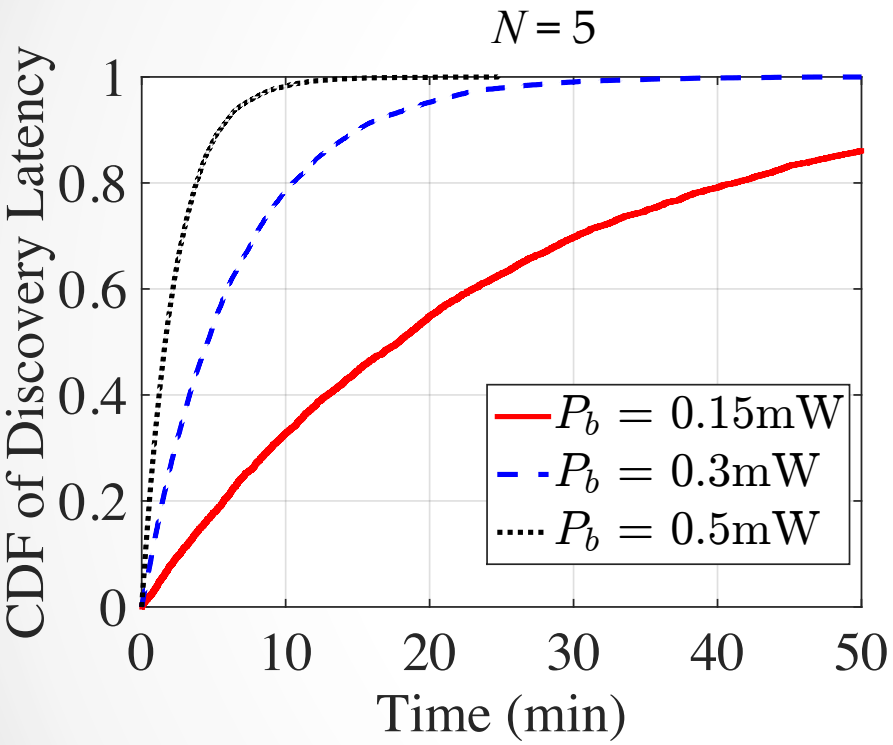
# Experimental Performance Evaluation: Discovery Rate

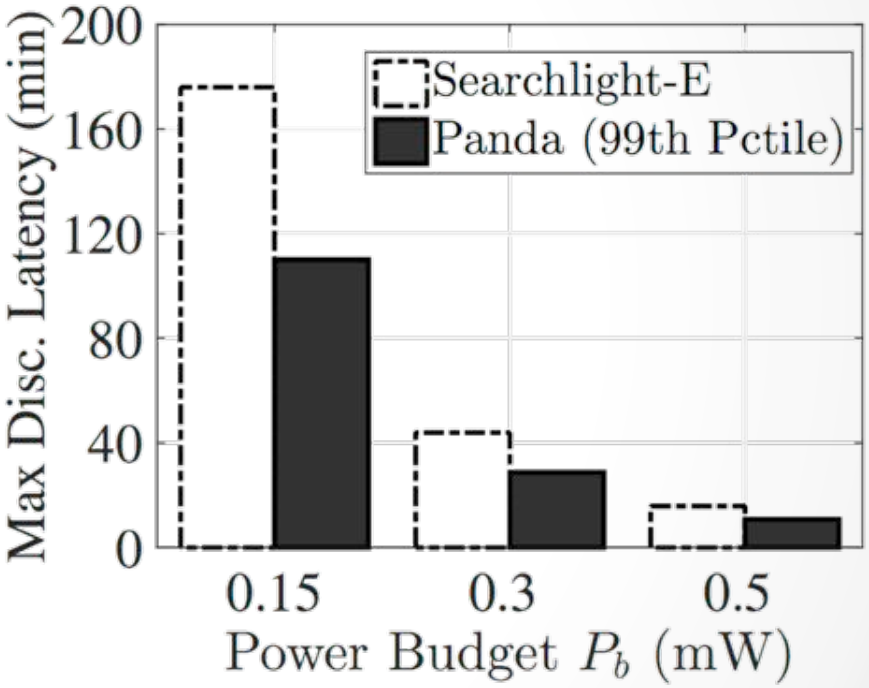



Discovery rate improves with number of nodes and power budget. Experimental accuracy over 98%.

# Experimental Performance Evaluation: Comparison to Related Works

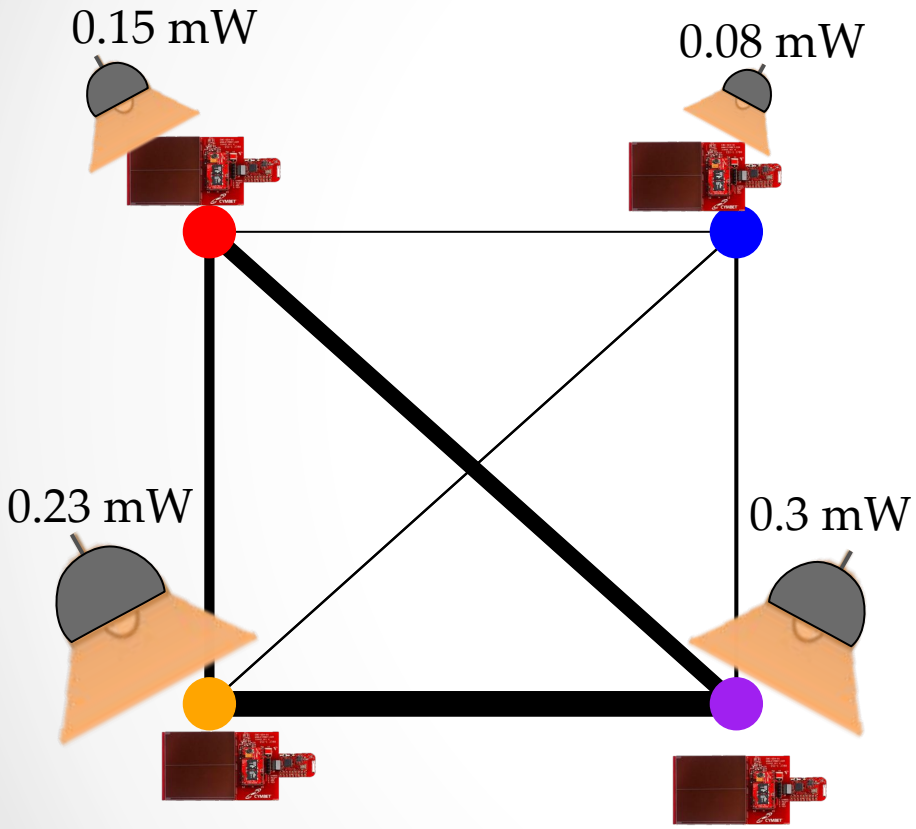


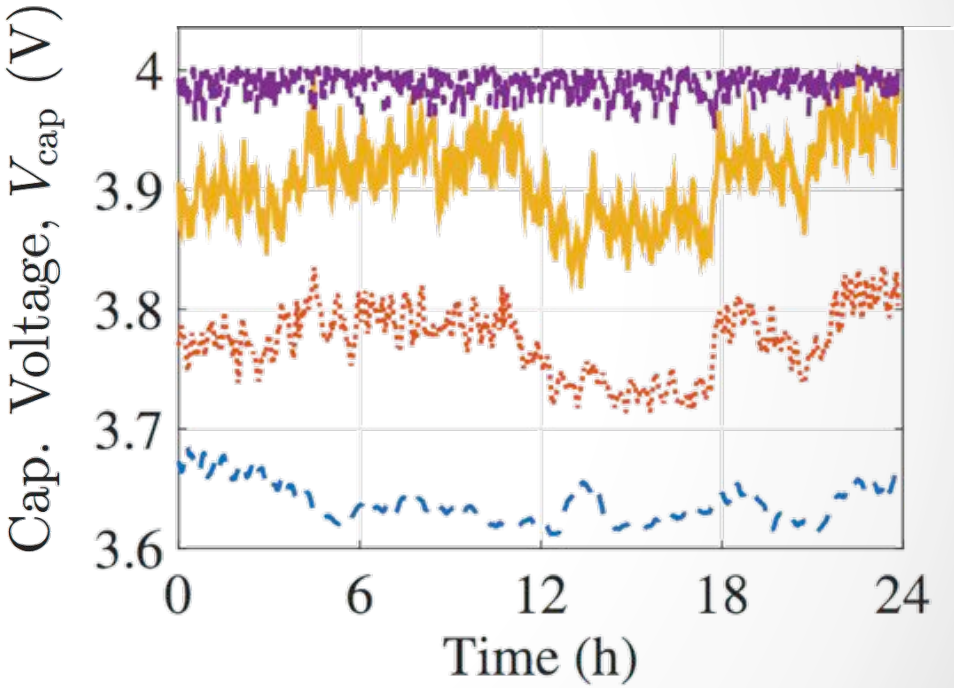




Outperform average discovery rates for related protocols by 2-3x, while maintaining better 99$^{th}$ quantile latency.

# Panda-D Performance Evaluation

- 4 nodes configured with Panda-D with varying light levels




* Line widths represent the discovery rate on each link

# Conclusions

- Objective: maximize the average discovery rate for energy harvesting nodes subject to a power budget
- Designed, analyzed, and evaluated the Panda protocol
- Experimental discovery rates are within 2% of theoretical estimates, demonstrating the practicality of the model
- Outperforms related work with a discovery rate that is up 3x higher
- Panda-D is able to adapt to scenarios with non-homogenous power harvesting