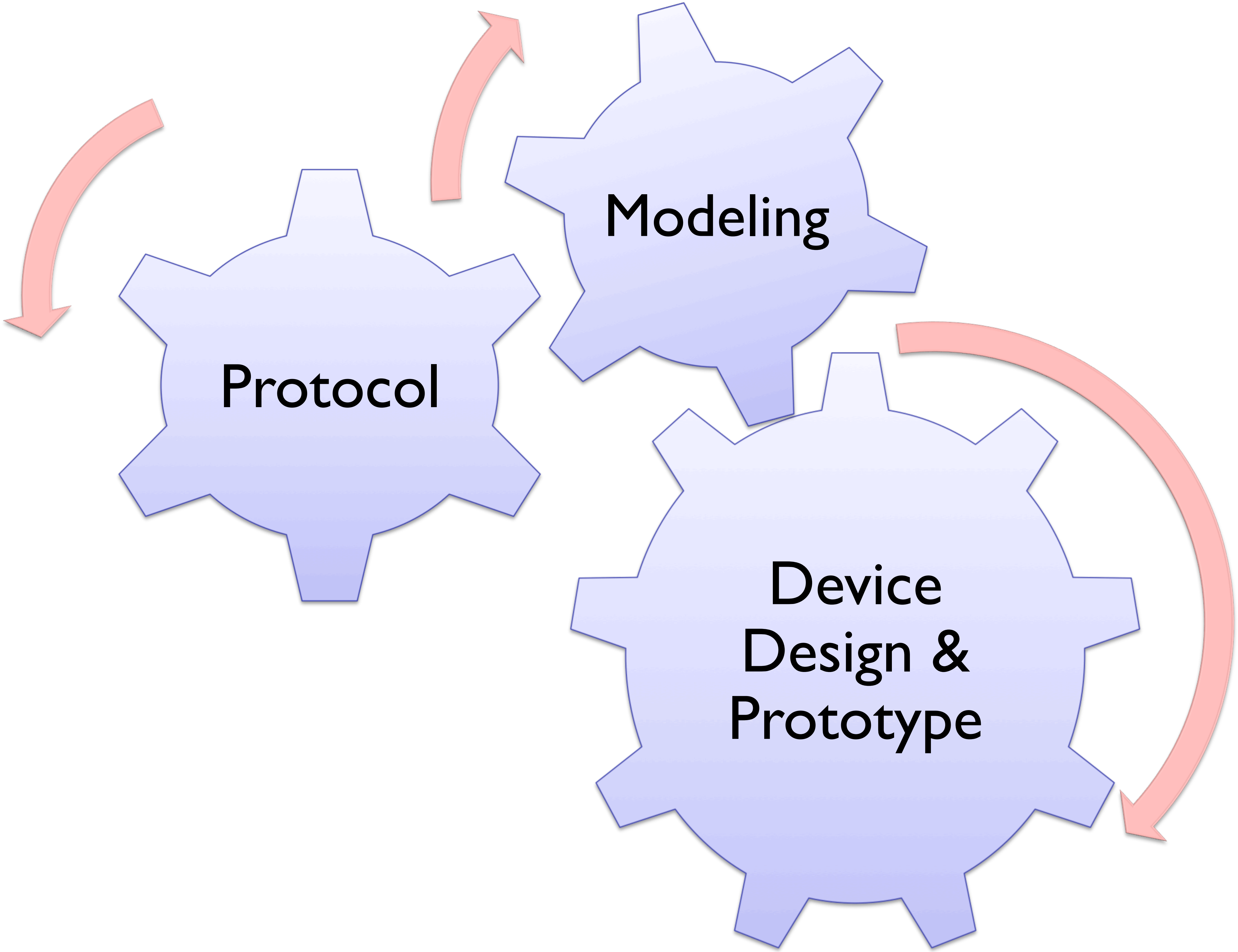
Energy Harvesting Wireless Sensor Networks: From Device Design to Deployment

Presented by:
Kaushik R. Chowdhury
krc@ece.neu.edu
Dept. of Electrical and Computer Engineering
Northeastern University
Boston, MA

Northeastern

Outline of Talk

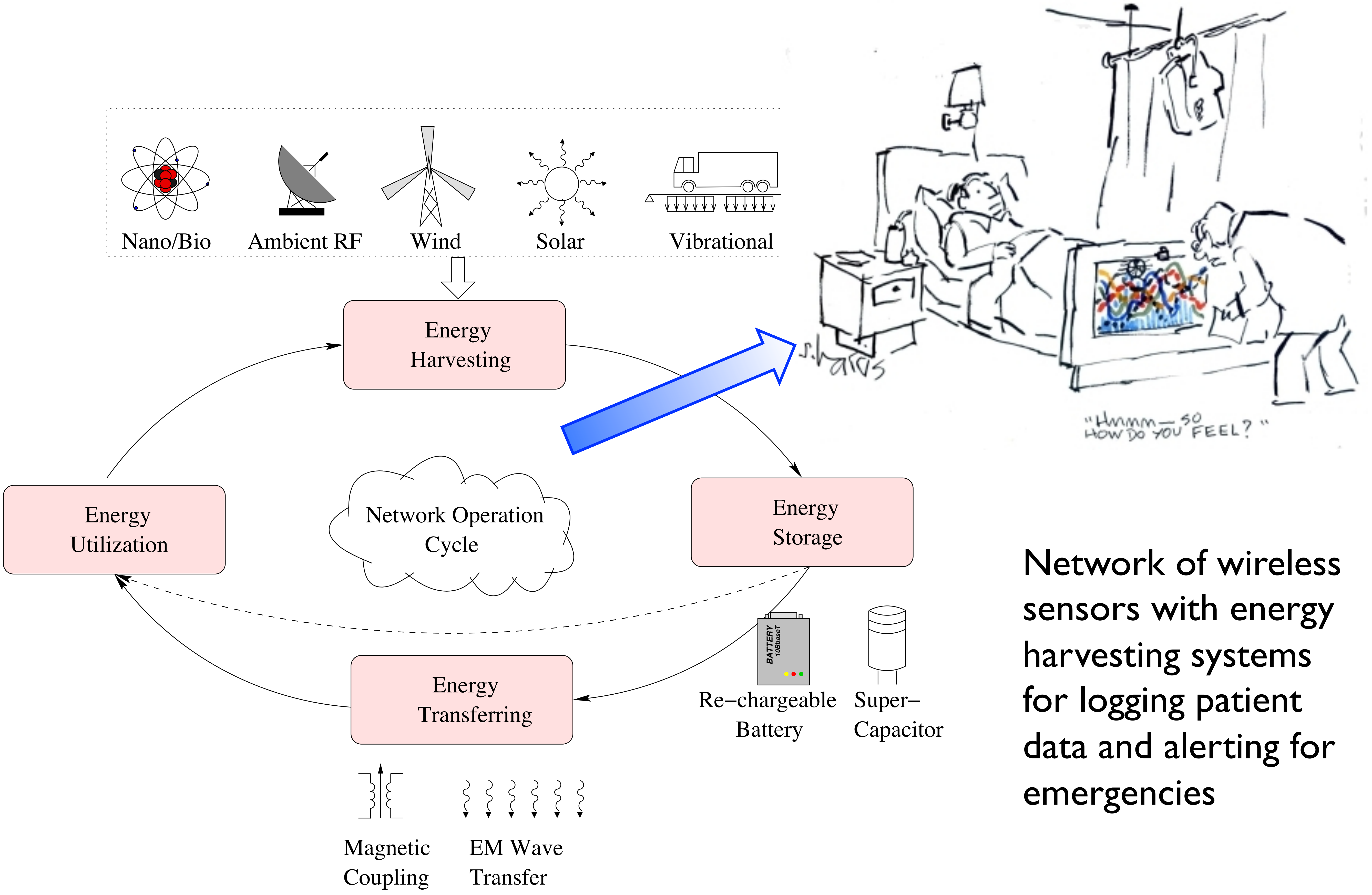


Protocol

Modeling

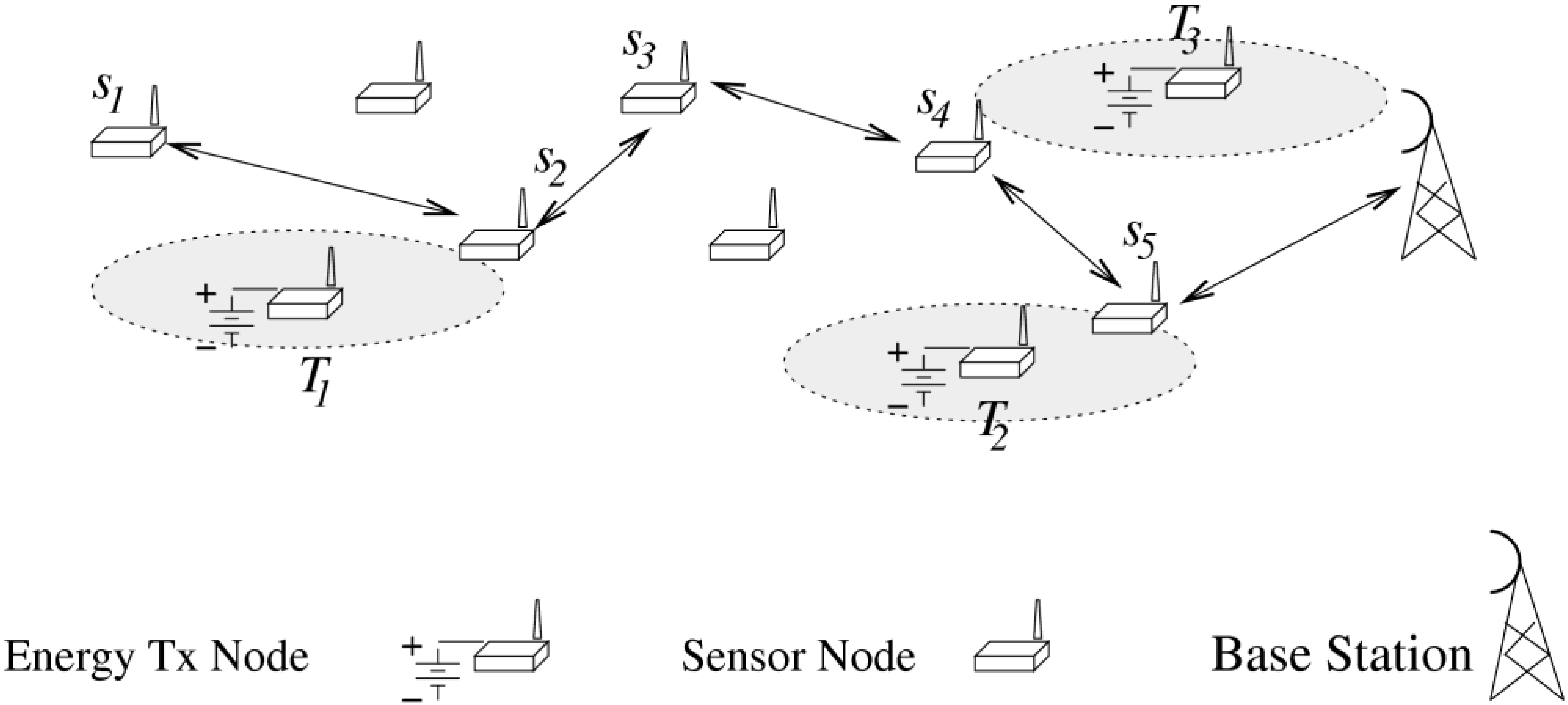
Device Design & Prototype

Energy Harvesting: Sources and Network Operations



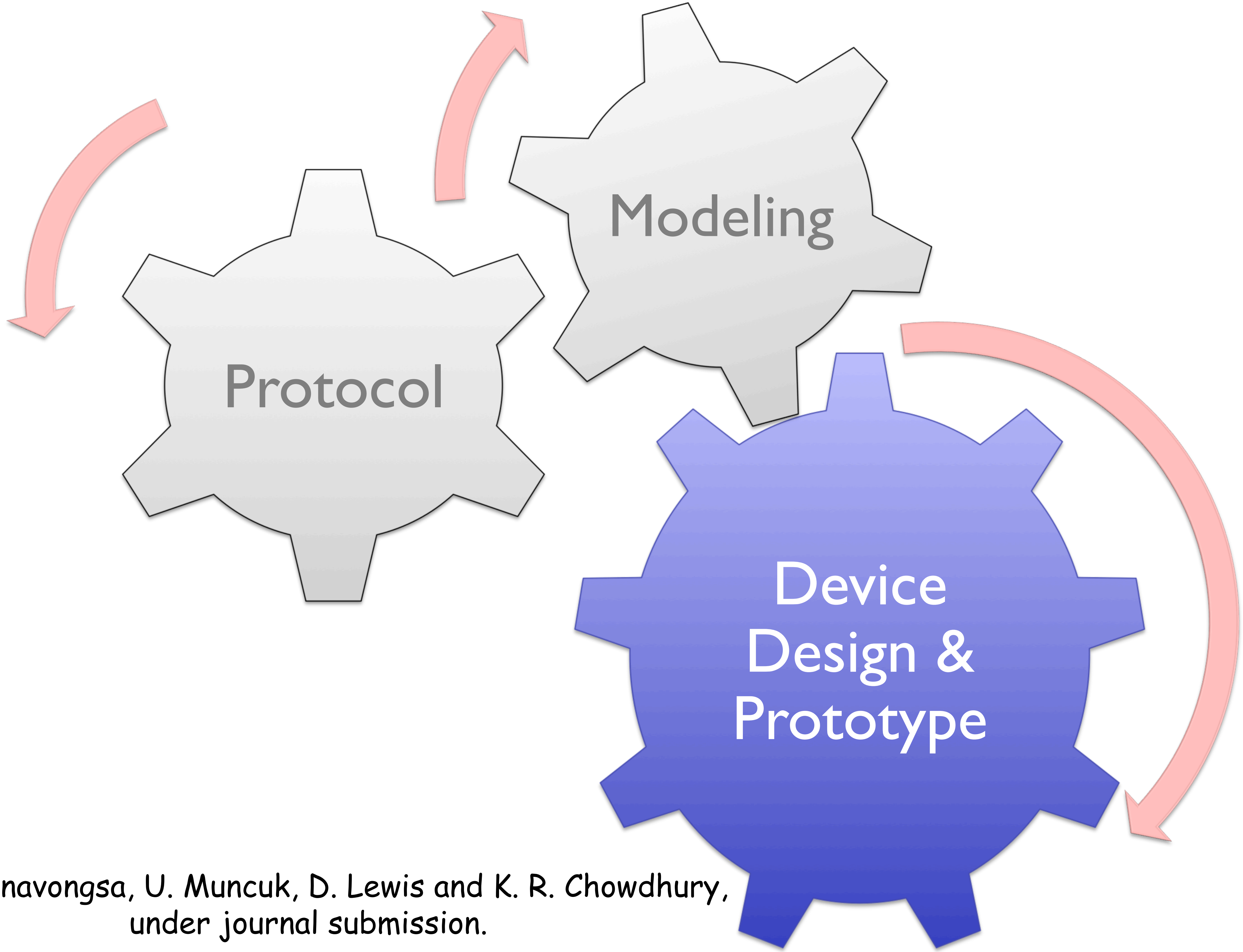
Network of wireless sensors with energy harvesting systems for logging patient data and alerting for emergencies

Energy Harvesting WSN: The larger picture



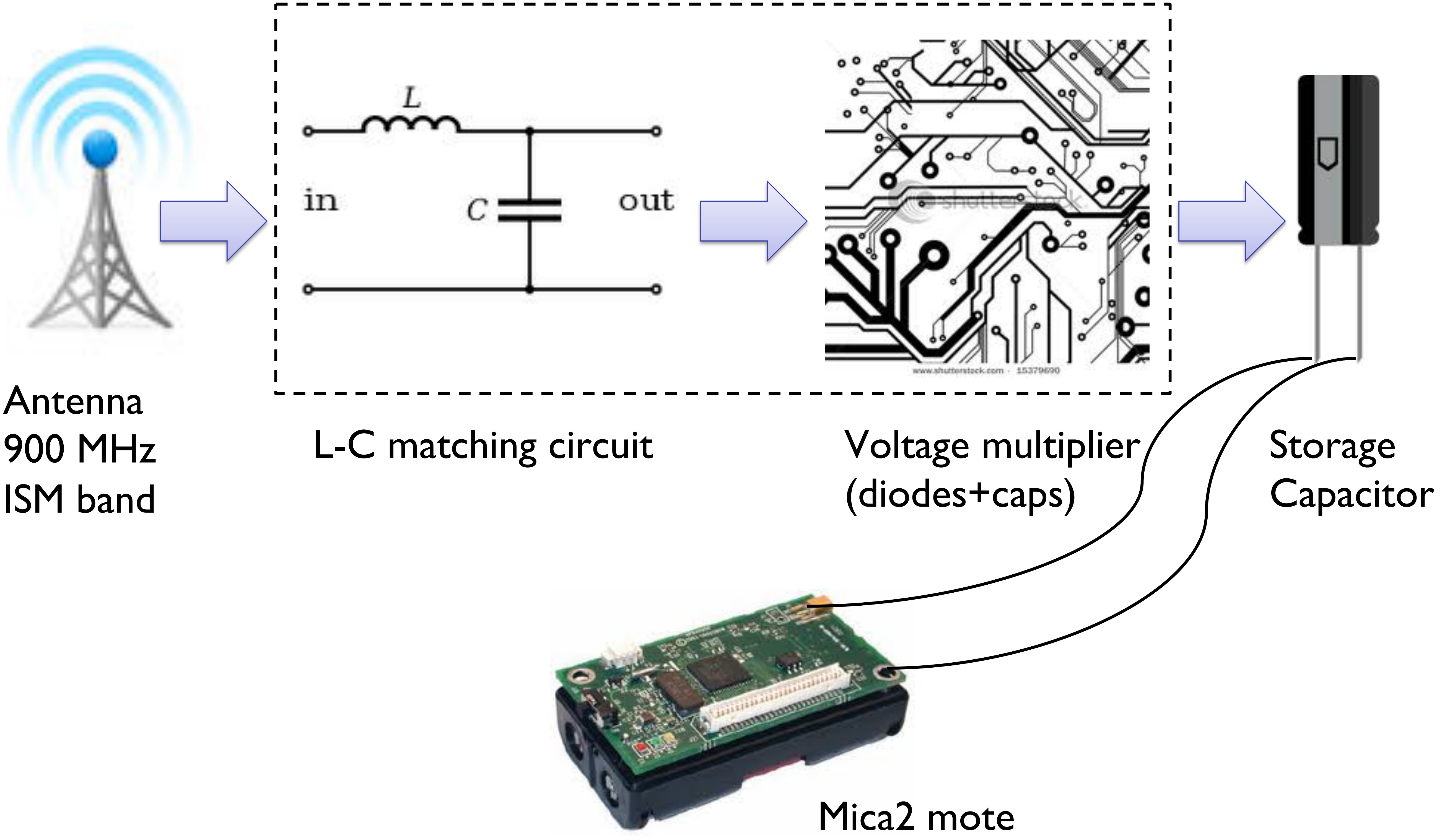
- T_1, T_2, … are connected to a power source.
- Charging EM waves are transmitted in 900 MHz band

Topics



P. Nintanavongsa, U. Muncuk, D. Lewis and K. R. Chowdhury, under journal submission.

Energy Harvesting Circuit



Antenna
900 MHz
ISM band

L-C matching circuit

Voltage multiplier
(diodes+caps)

Storage
Capacitor

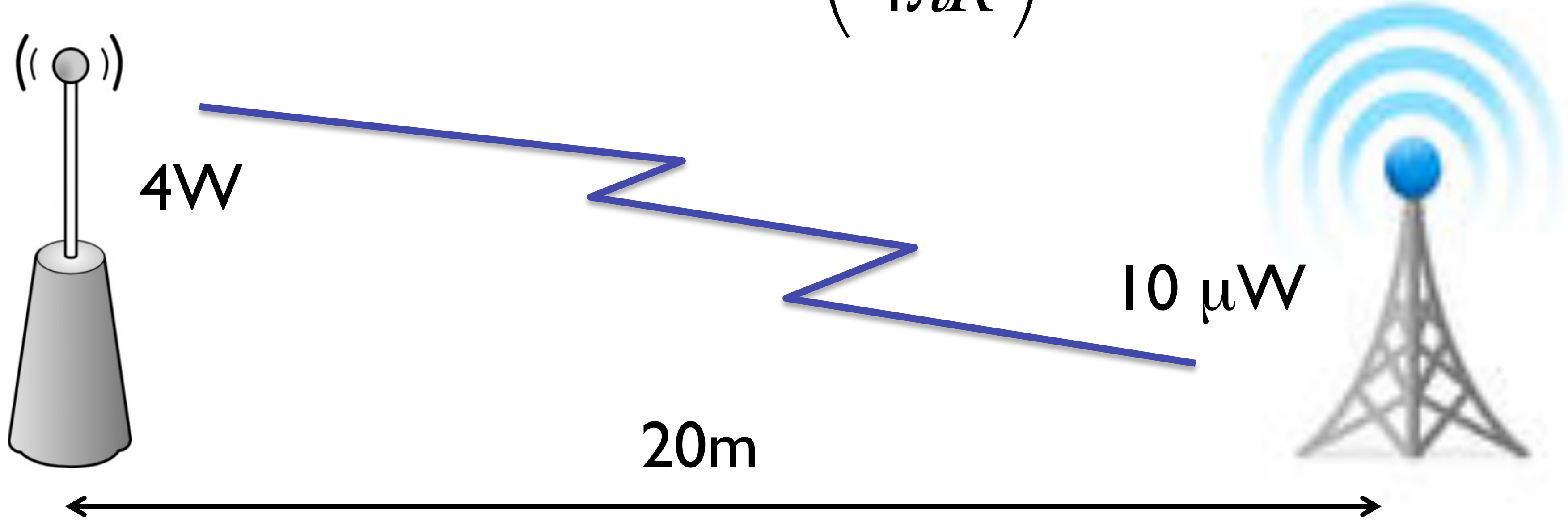
Mica2 mote

900 MHz ISM band

Energy Harvesting Circuit

How much power do we get at the antenna?

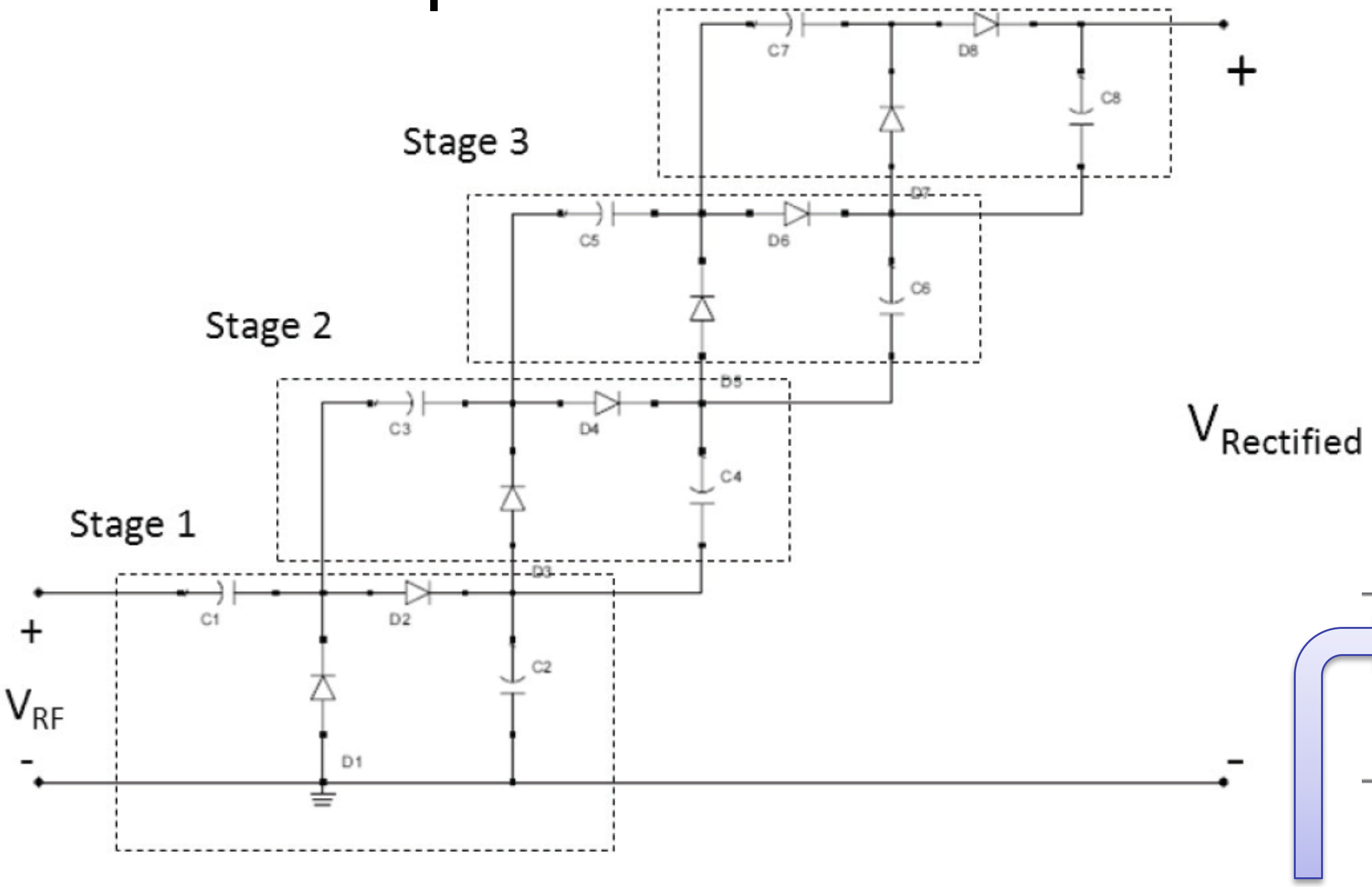
$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$



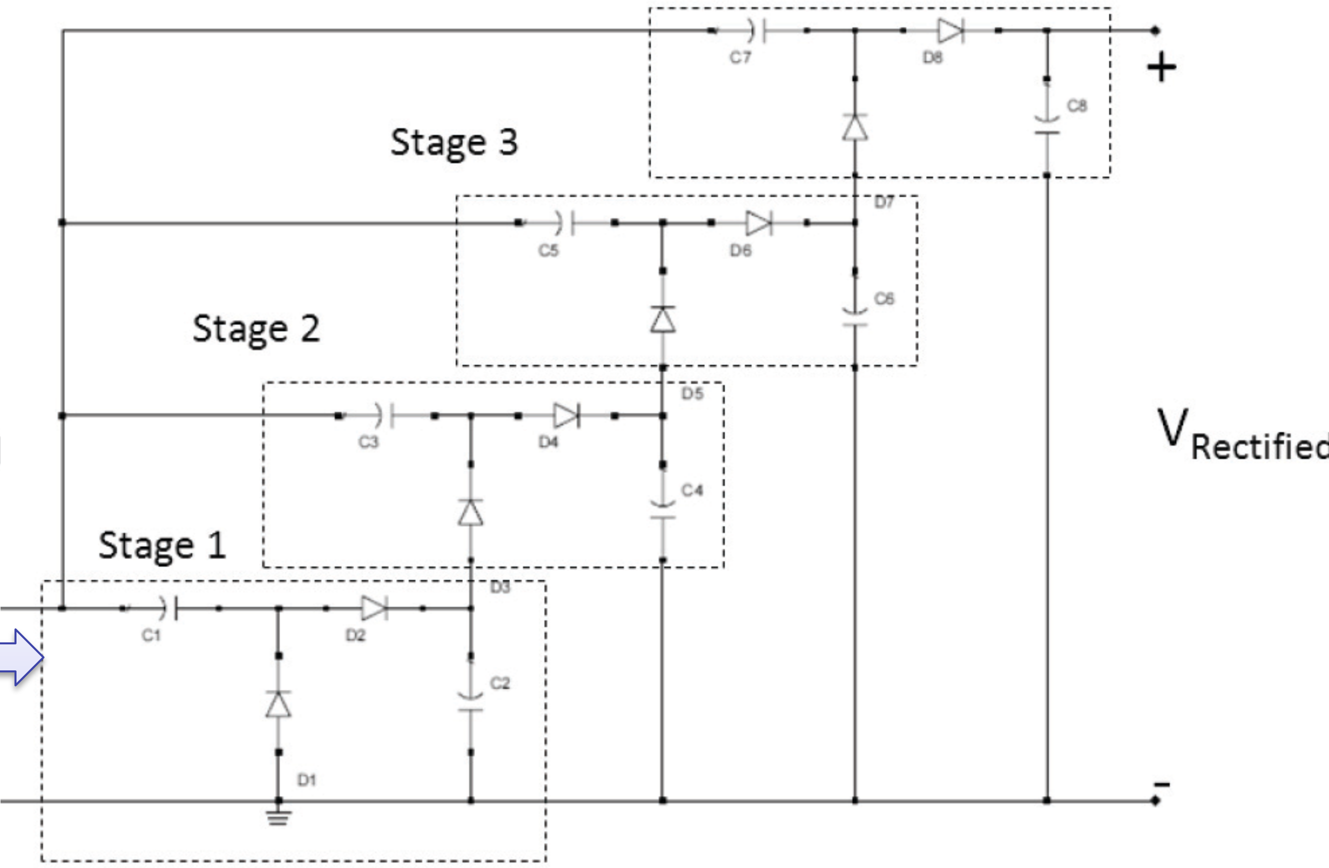
- 32 mV seen at 50Ω antenna at -20 dBm received RF, operating at 915 MHz
  - Diodes with low turn on voltage needed
  - Fast switching diodes needed

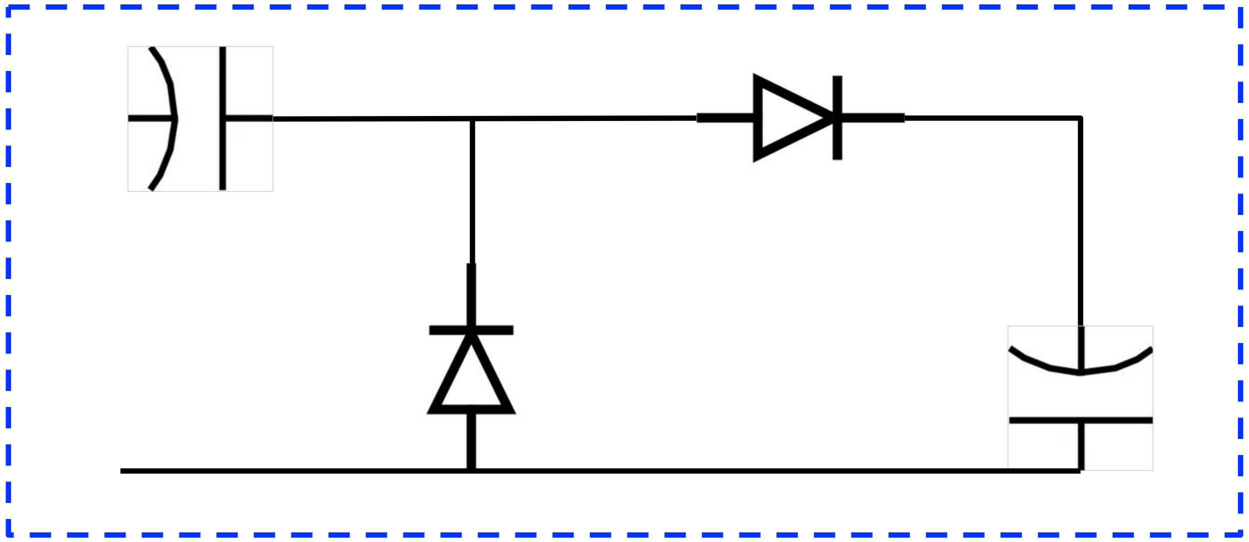
Voltage Multiplier

Villard Multiplier



Dickson Multiplier





A “stage”

H. Yan, J.G. Macias Montero, A. Akhnoukh, L.C.N. de Vreede and J.N. Burghart, An Integration Scheme for RF Power Harvesting. *8th Annual Workshop on Semiconductor Advances for Future Electronics and Sensors, Veldhoven, the Netherlands, 2005.*

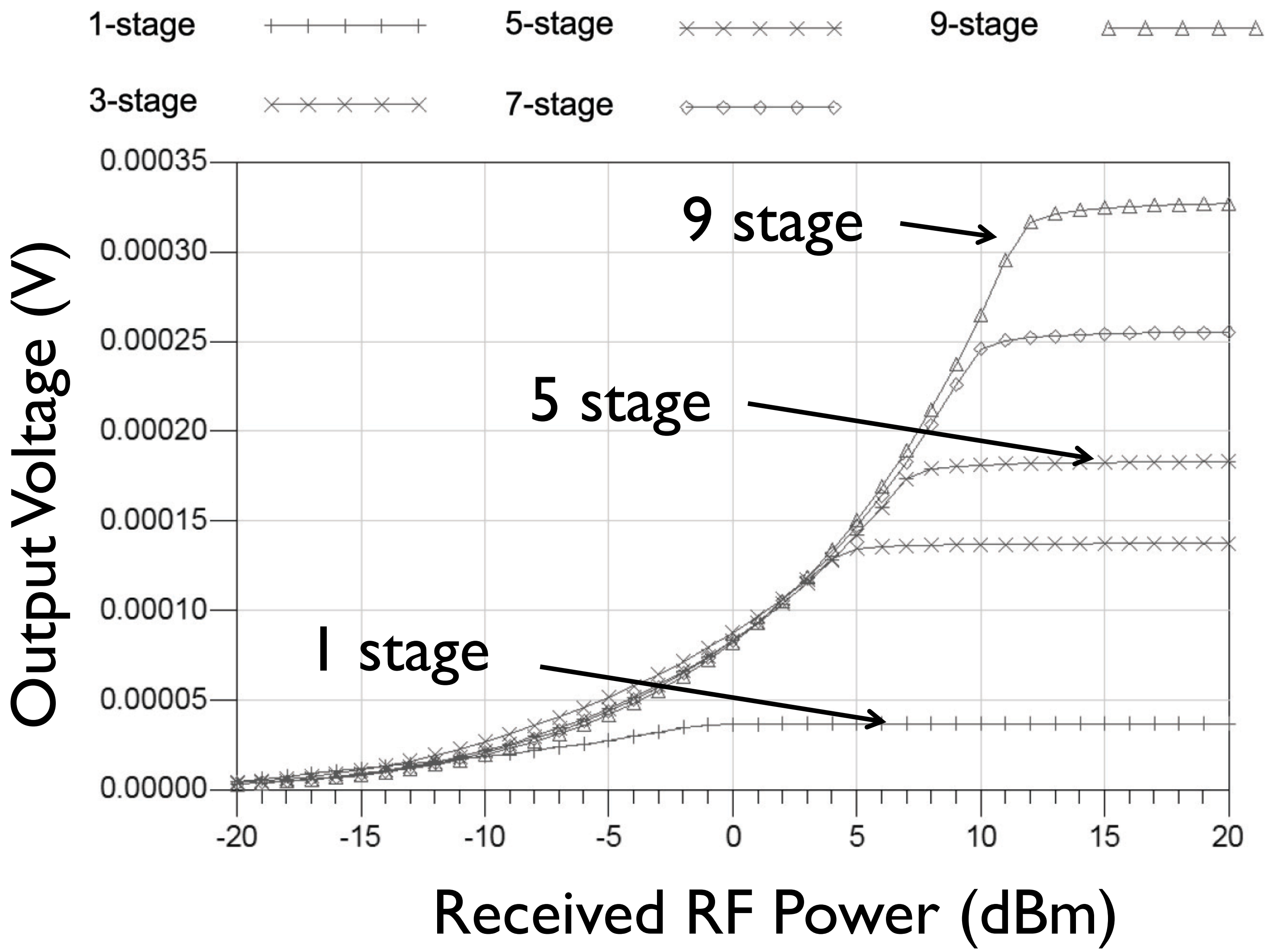
Efficiency of EH Circuit

$$\eta_c = \frac{DC\ output\ power}{incident\ RF\ power - reflected\ RF\ power}$$

$$\eta_o = \frac{DC\ output\ power}{incident\ RF\ power}$$

- Conversion efficiency η_c does not take impedance mismatch into the account
- Overall efficiency η_o provides a complete representation of the energy harvesting circuit performance

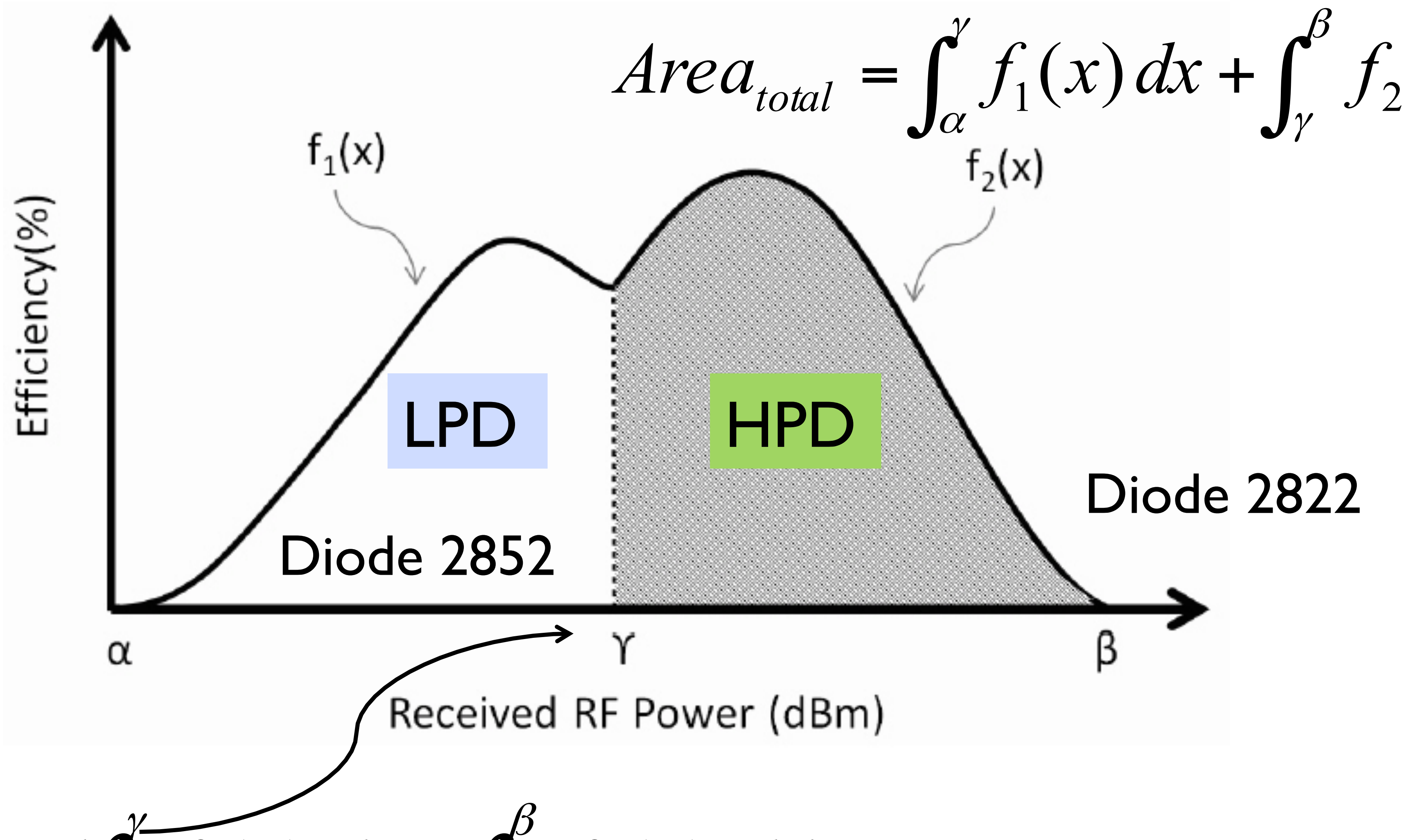
Effect of Number of stages



- Each stage here is a modified voltage multiplier, arranged in series
- Higher voltage can be achieved by increasing number of circuit stages
- Voltage gain decreases with increasing number of stages

Optimization Framework

$$Area_{total} = \int_{\alpha}^{\gamma} f_1(x)\,dx + \int_{\gamma}^{\beta} f_2(x)\,dx$$



$$\gamma = \arg\max_{\gamma} \{\int_{\alpha}^{\gamma} f_1(x)\,dx + \int_{\gamma}^{\beta} f_2(x)\,dx\}$$

- Maximize the efficiency throughout the range of α dBm to β dBm, subject to several device and performance constraints
- This optimization exhibits the optimal substructure property

Optimization Framework

$$\gamma = \arg\max_{\gamma}\{\int_{\alpha}^{\gamma} f_1(N_1, L, C, x)\,dx + \int_{\gamma}^{\beta} f_2(N_2, L, C, x)\,dx\}$$

- Efficiency curve is a function of
  - Matching network: L, C
  - Number of stages: N

$Given : L, C, N$ ← Given limiting conditions

$To\ find : \gamma, N_1, N_2$ ← Find crossover point (γ) and number of stages in both sub-circuits

$To\ Maximize :$

$$Area_{total} = \int_{\alpha}^{\gamma} f_1(N_1, L, C, x)\,\mathrm{d}x + \int_{\gamma}^{\beta} f_2(N_2, L, C, x)\,\mathrm{d}x$$

Optimization Framework

Efficiency curves should not overlap completely

$$\mathit{Subject\ to:}$$

$$\int_{\alpha}^{\gamma} f_1(N_1, L, C, x)\,\mathrm{d}x > \int_{\gamma}^{\beta} f_1(N_1, L, C, x)\,\mathrm{d}x \ \mathit{and}$$

$$\int_{\gamma}^{\beta} f_2(N_2, L, C, x)\,\mathrm{d}x > \int_{\alpha}^{\gamma} f_2(N_2, L, C, x)\,\mathrm{d}x$$

$$\forall\, x : I(x + \Delta x) \geq I(x)$$

Monotonic increase of current

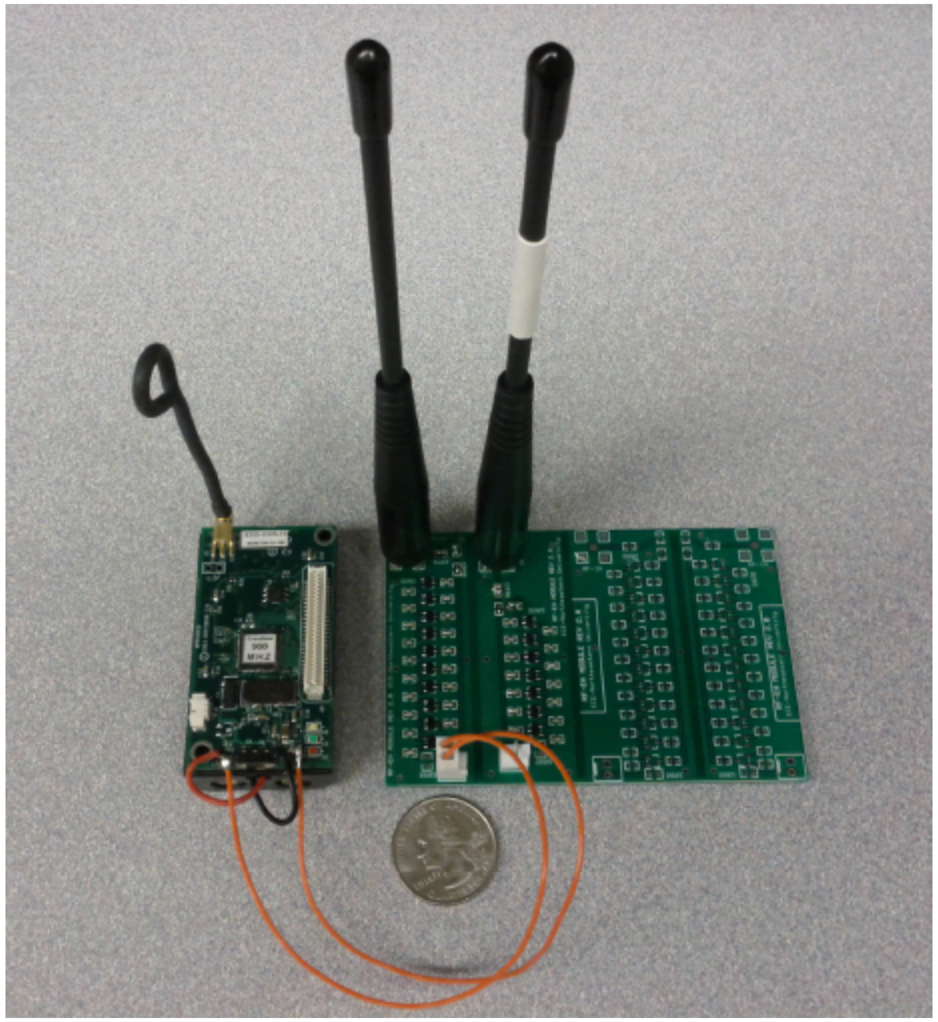
$$\forall\, x : V(x + \Delta x) \geq V(x)$$

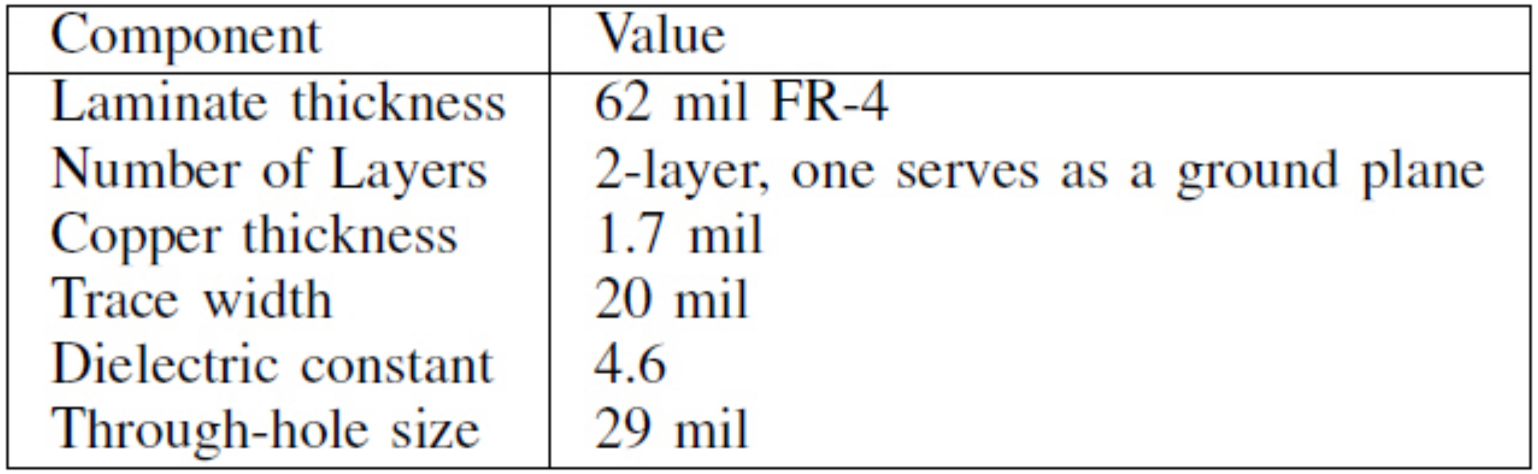
Monotonic increase of voltage

$$V(x = -10) \geq 1.8\ v.$$

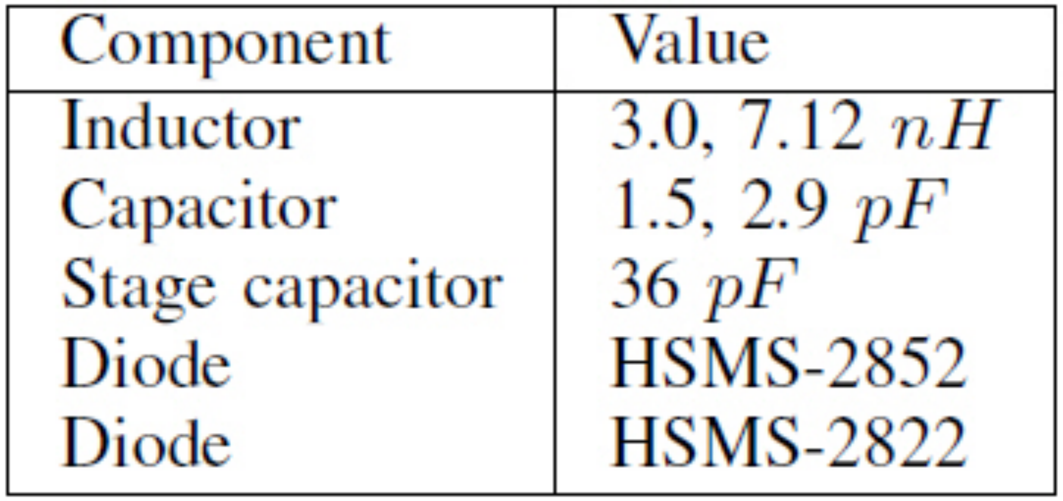
Sensor mote lowest operating voltage

Fabrication of Energy Harvesting Circuit





Component	Value
Laminate thickness	62 mil FR-4
Number of Layers	2-layer, one serves as a ground plane
Copper thickness	1.7 mil
Trace width	20 mil
Dielectric constant	4.6
Through-hole size	29 mil



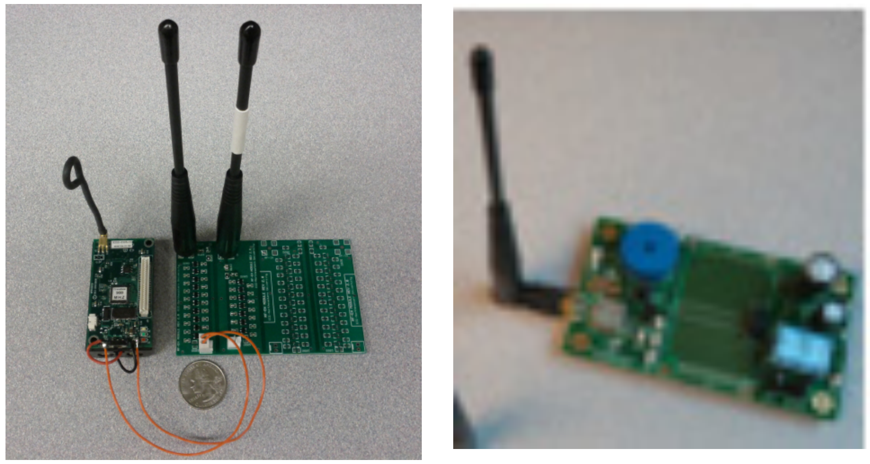
Component	Value
Inductor	3.0, 7.12 nH
Capacitor	1.5, 2.9 pF
Stage capacitor	36 pF
Diode	HSMS-2852
Diode	HSMS-2822

- Parameters obtained from the optimization framework
- 7-stage HSMS-2852 for LPD and 10-stage HSMS-2822 for HPD

Performance Evaluation

915 MHz RF, -20 dBm to 20 dBm

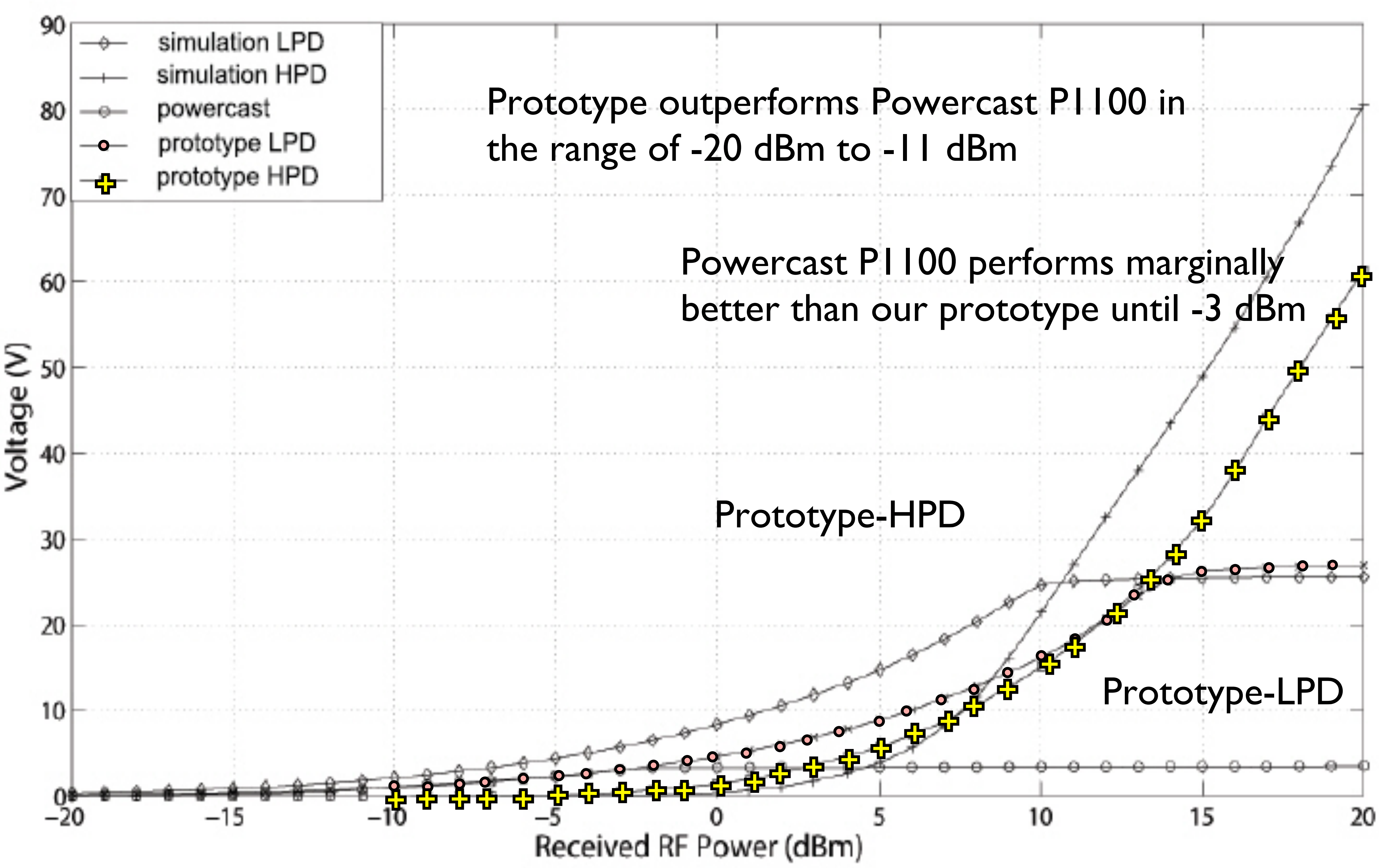
Device Under Test (DUT)
- Prototype
- Powercast P1100



Performance assessment
- Voltage
- Efficiency

- Powercast P1100 evaluation board
- 100KΩ resistive load
- RF power from -20 dBm to 20 dBm
- Voltage and efficiency comparison

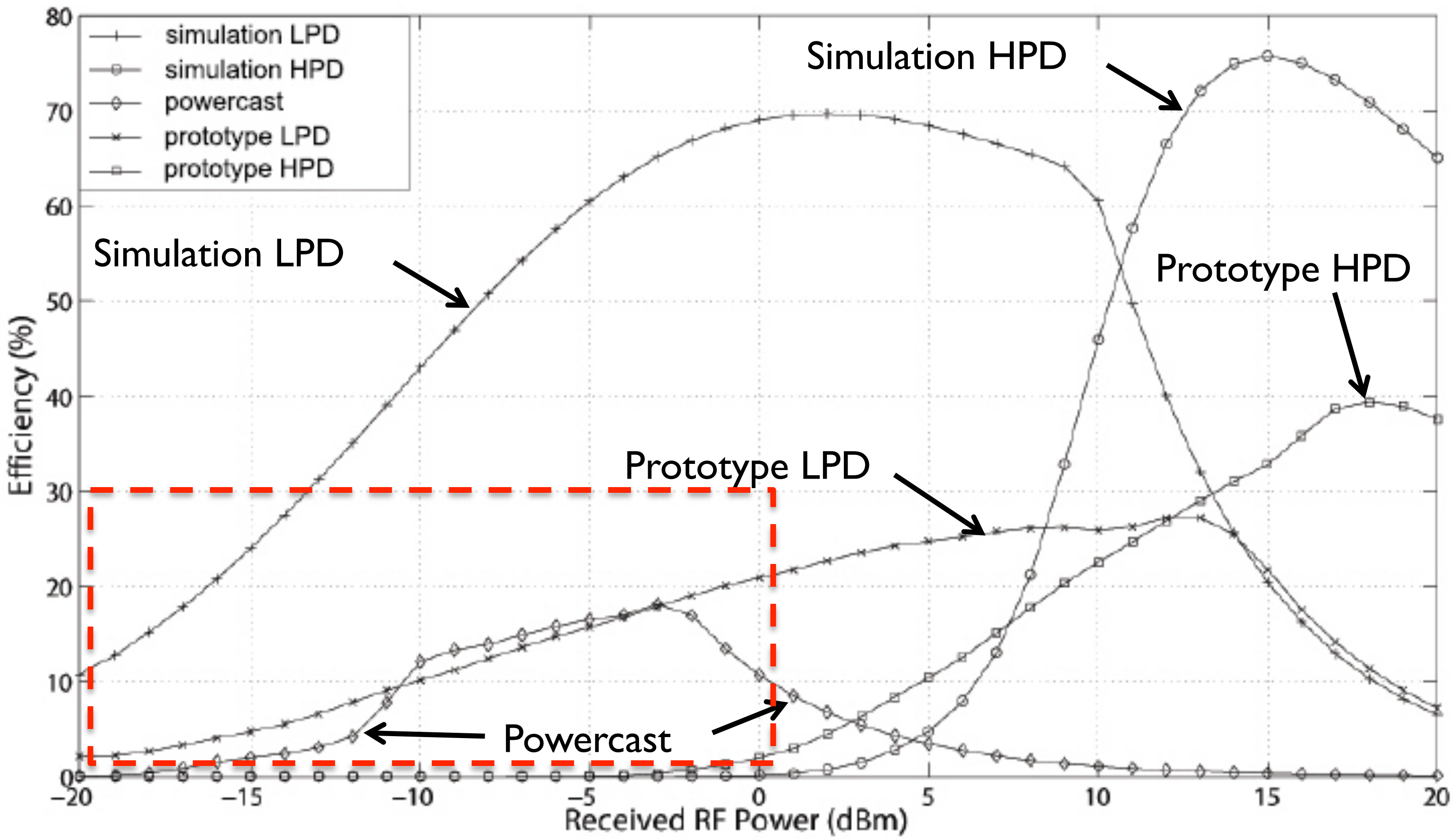
Performance Evaluation



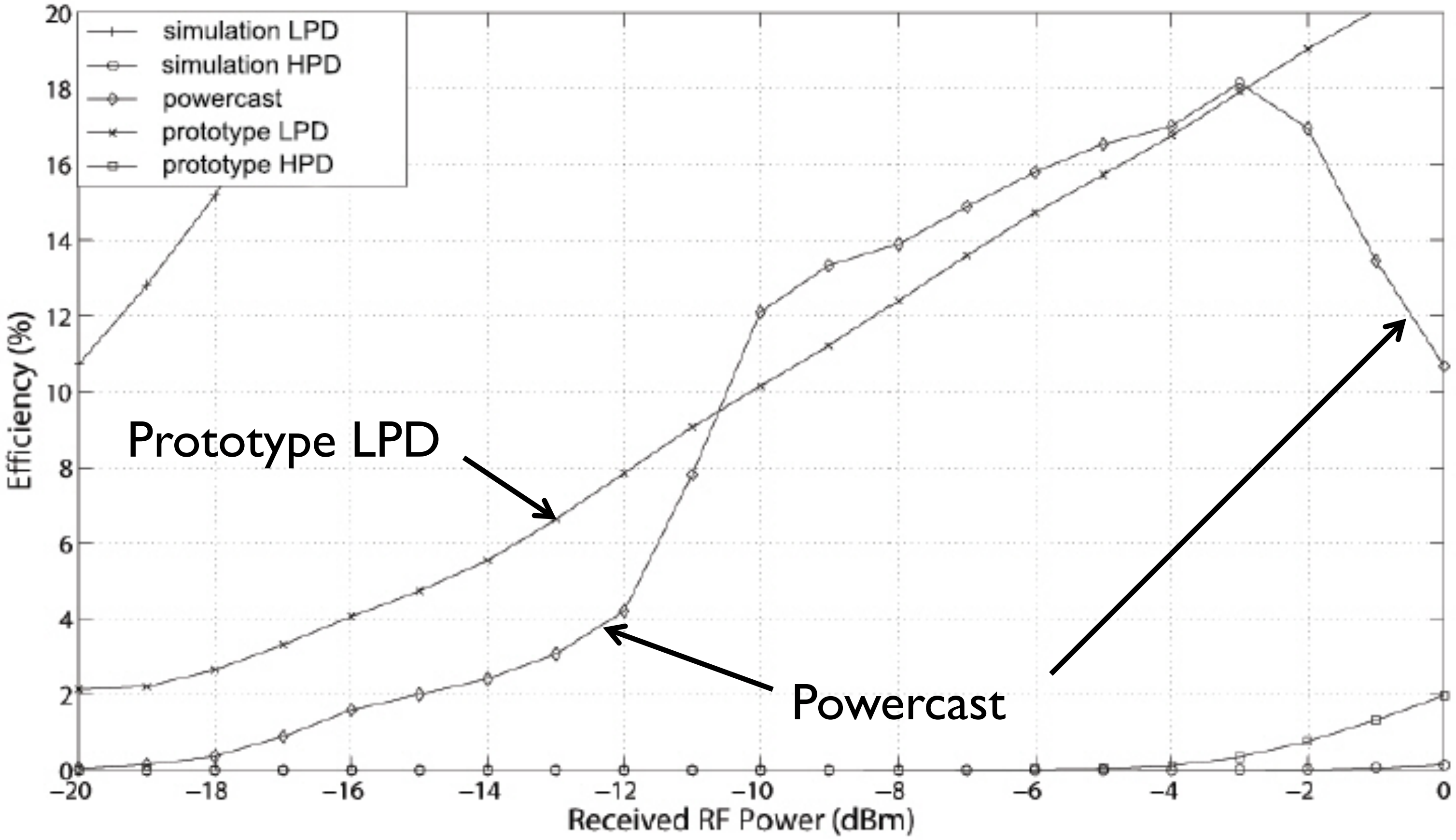
Prototype outperforms Powercast P1100 in the range of -20 dBm to -11 dBm

Powercast P1100 performs marginally better than our prototype until -3 dBm

Performance Evaluation

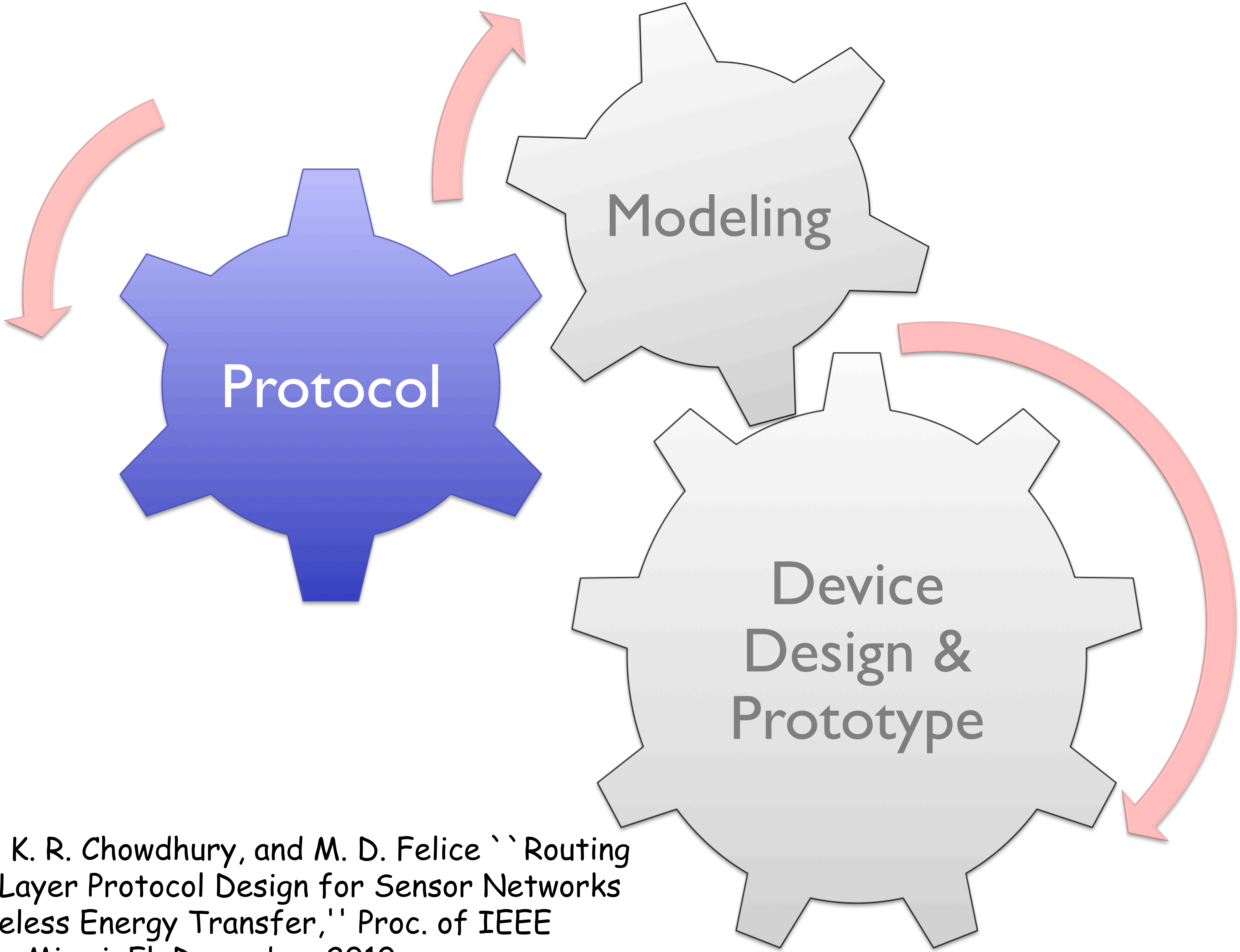


Prototype outperforms Powercast P1100 in the range of -20 dBm to -11 dBm



Powercast P1100 performs marginally better than our prototype until -3 dBm

Topics



Protocol

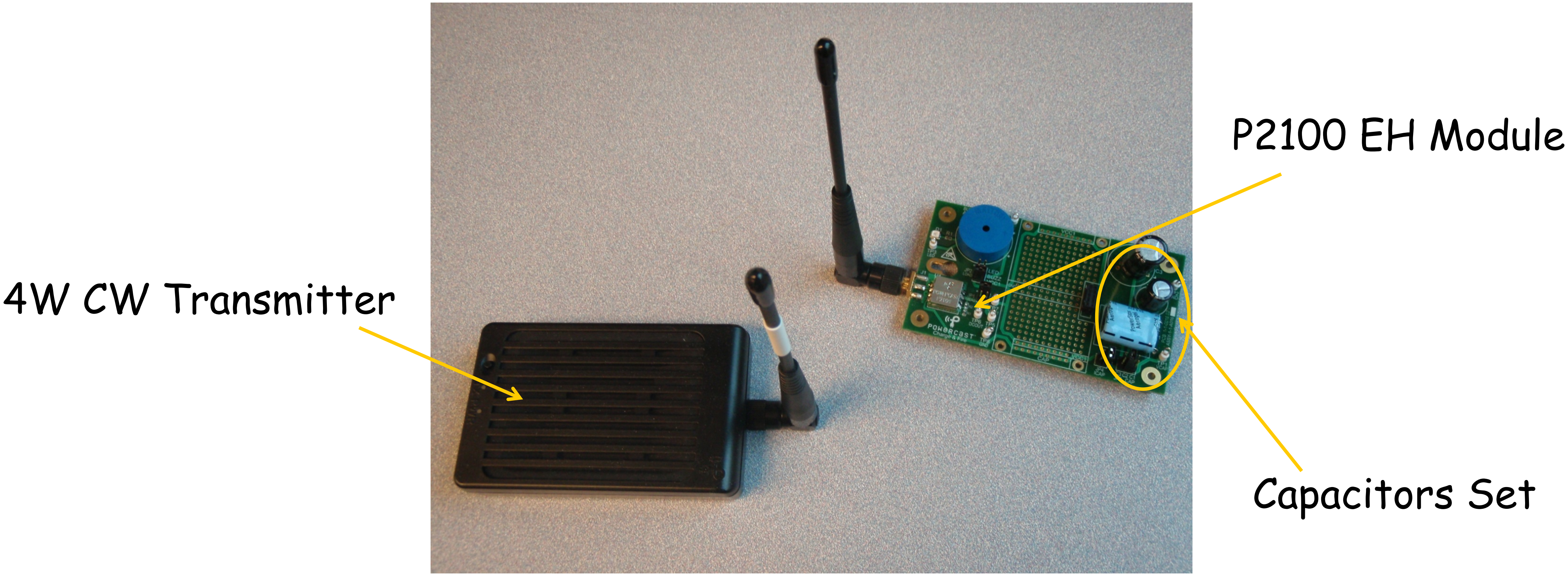
Modeling

Device Design & Prototype

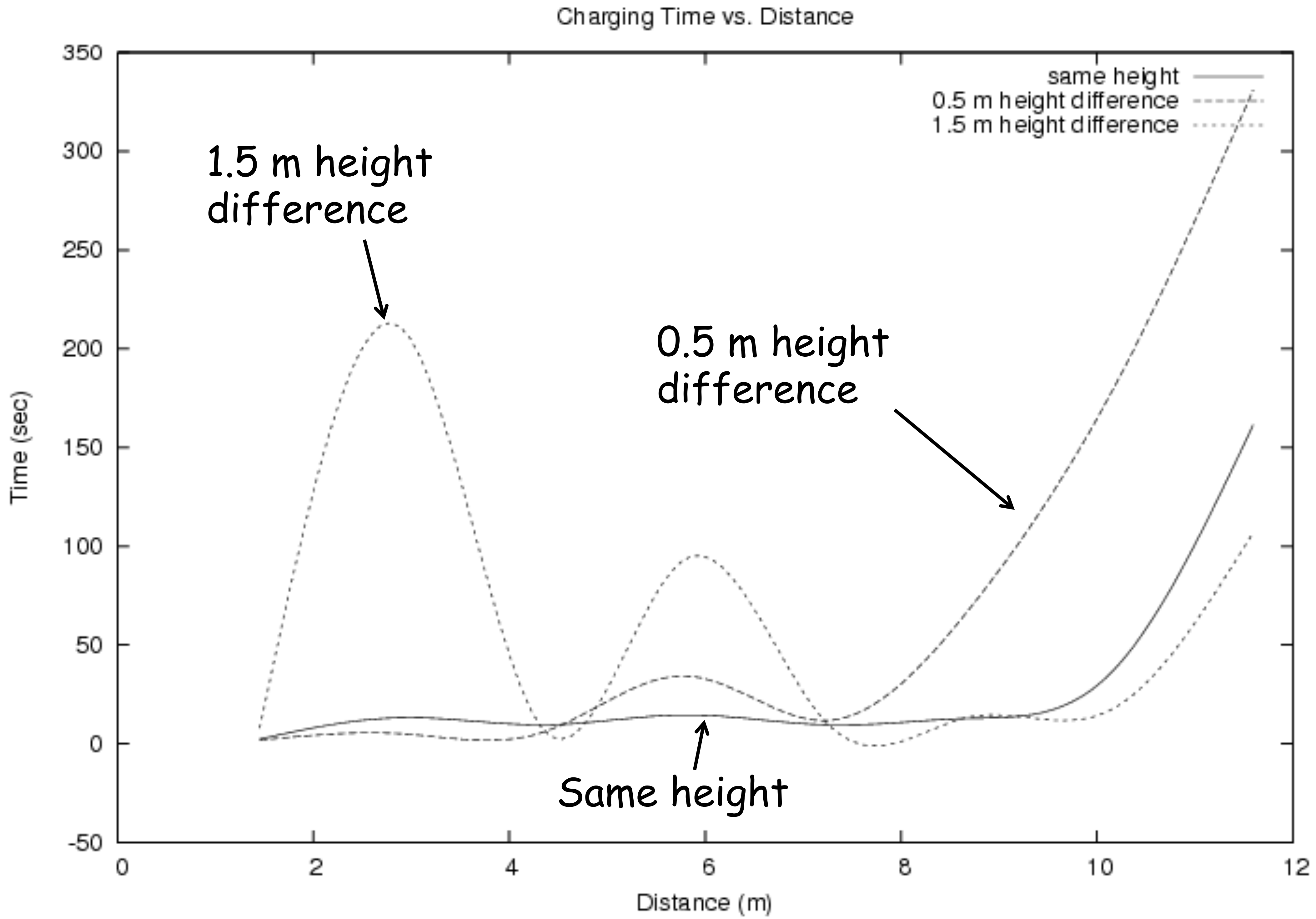
R. Doost, K. R. Chowdhury, and M. D. Felice ``Routing and Link Layer Protocol Design for Sensor Networks with Wireless Energy Transfer,'' Proc. of IEEE Globecom, Miami, Fl, December 2010

Energy Harvesting Module

- P2100 energy harvesting module from Powercast, converts energy of a signal received from a 4 Watt CW transmitter to DC voltage in a 1mF capacitor up to 1.16V.



Energy Harvesting Performance



- For distances greater than 12m, charging time is infinite.
- The general trend is towards increasing Ch. Time with distance
- Height difference, adds considerable fluctuations to Ch. time

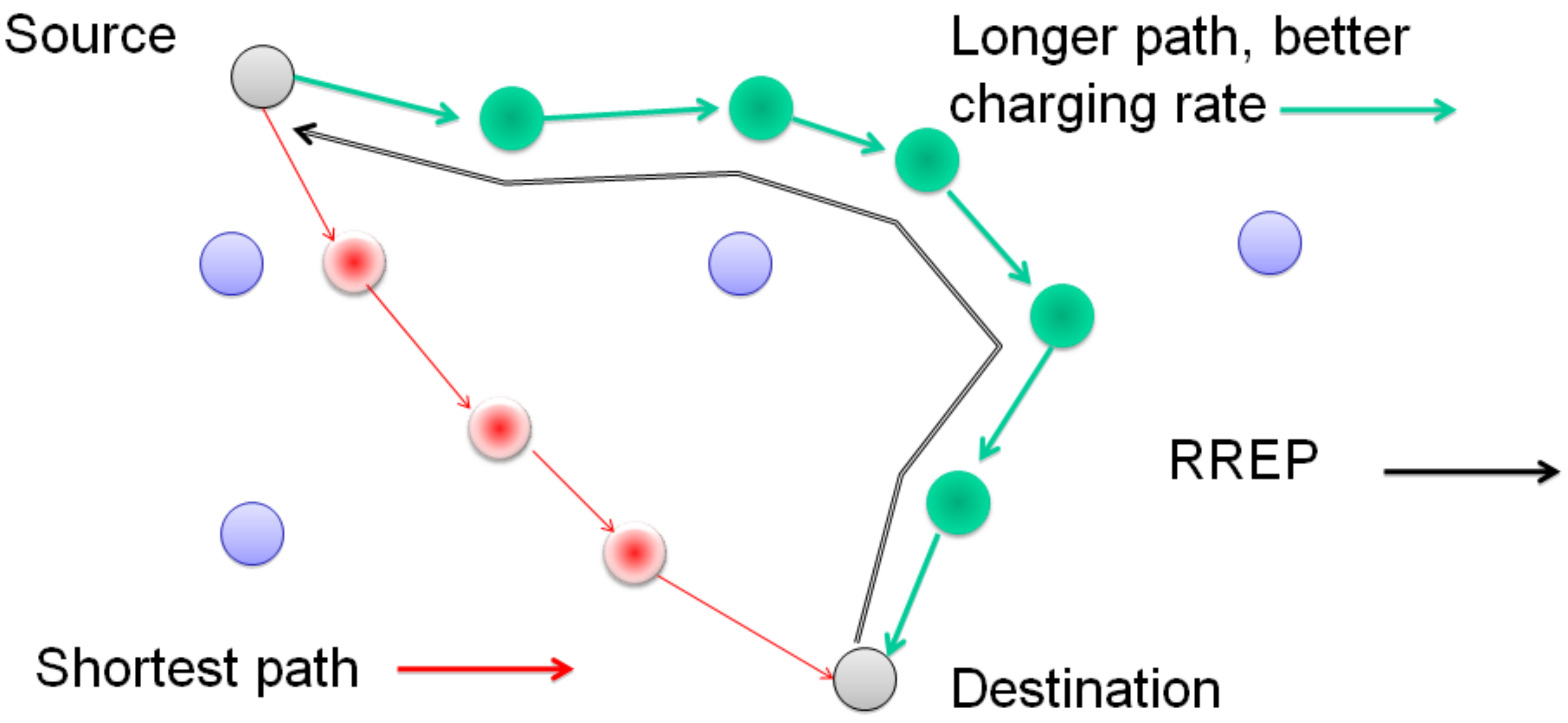
Motivations for Routing Layer Adaptation

- Wireless Energy Transfer may give rise to a new class of sensor networks that allows the sensors to be charged on the field, thereby prolonging the lifetime.

- Protocols like AODV choose the shortest path in term of the hop count for delivering the packets.

- Shortest path may not be the best choice for packet delivery in energy harvesting sensor network, since not all the nodes experience the same charging rate.

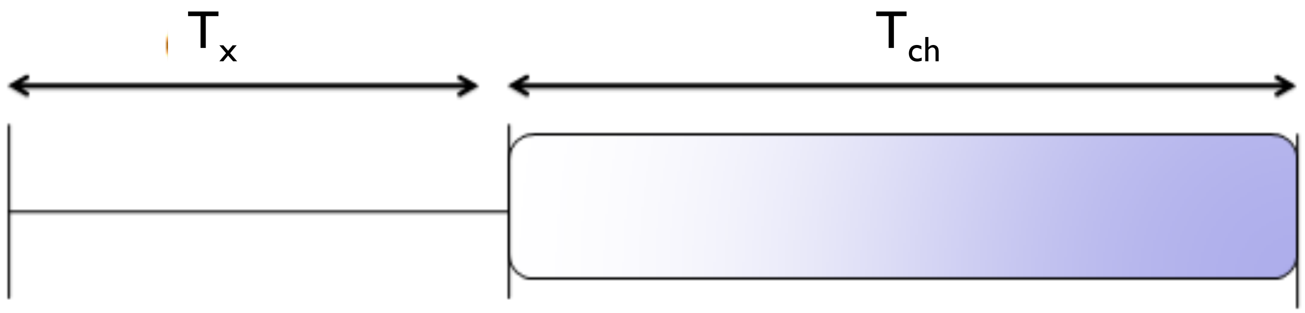
Routing Metric



- A metric other than hop count must be considered for routing. We propose the tuple of the max. charging time and deviation of all the nodes of the path $< T_{ch}^{\max}(k), \eta_c^{\max} h(k) >$
- At startup, ETs transmit for a pre-determined duration, allowing nodes to measure their charging time t_{ch}^{i} and their STD η_{ch}^{i} over multiple trials.

Duty Cycle at the Link Layer

- Energy and Data transmission are happening on the same band.
- Scheduling data transmission time (T_x) charging time (T_{ch}) is imperative to avoid interference.
- T_x is constrained by the amount of harvested energy during T_{ch} (Energy Neutrality)
- Latency requirements of the network must be satisfied by having the proper data rate and T_x time



Optimization Framework for Link Layer

$$Given : L_{lim}, ESR_{lim}, N$$

← Given limiting conditions

$$To\ find : T_{ch}, T_{frame}$$

← Find the charging time (T_{ch}) and frame time (T_{frame})

$$To\ Maximize : Throughput = \frac{T_x \cdot R}{T_{frame}}$$

To maximize the throughput as a fractional transmission rate during the frame

N: total number of nodes in the path
L_{lim}: Latency limit
R: Tx rate
ESR_{lim}: Capacitor quality metric limit

Optimization Framework for Link Layer

Ideal case: Harvested energy should be enough to meet Tx requirements

$$\textit{Subject to}:$$

$$(E_{rec} - E_{idle}) \cdot T_{ch} - E_{tx} \cdot T_x \geq 0$$

$$N\left(T_{ch} + \frac{P+H}{R}\right) \leq L_{lim}$$

End-to-End latency of a packet for N-hop route must be below L_{lim}

$$\frac{1}{ESR_0}\left[1 - k \cdot t \cdot \exp^{\frac{-4700}{T+273}}\right] > \frac{1}{ESR_{lim}}$$

$$T_{frame} = T_x + T_{ch}$$

Capacitor lifetime – charge/discharge cycles shoul
not cause ESR_{lim} to exceed

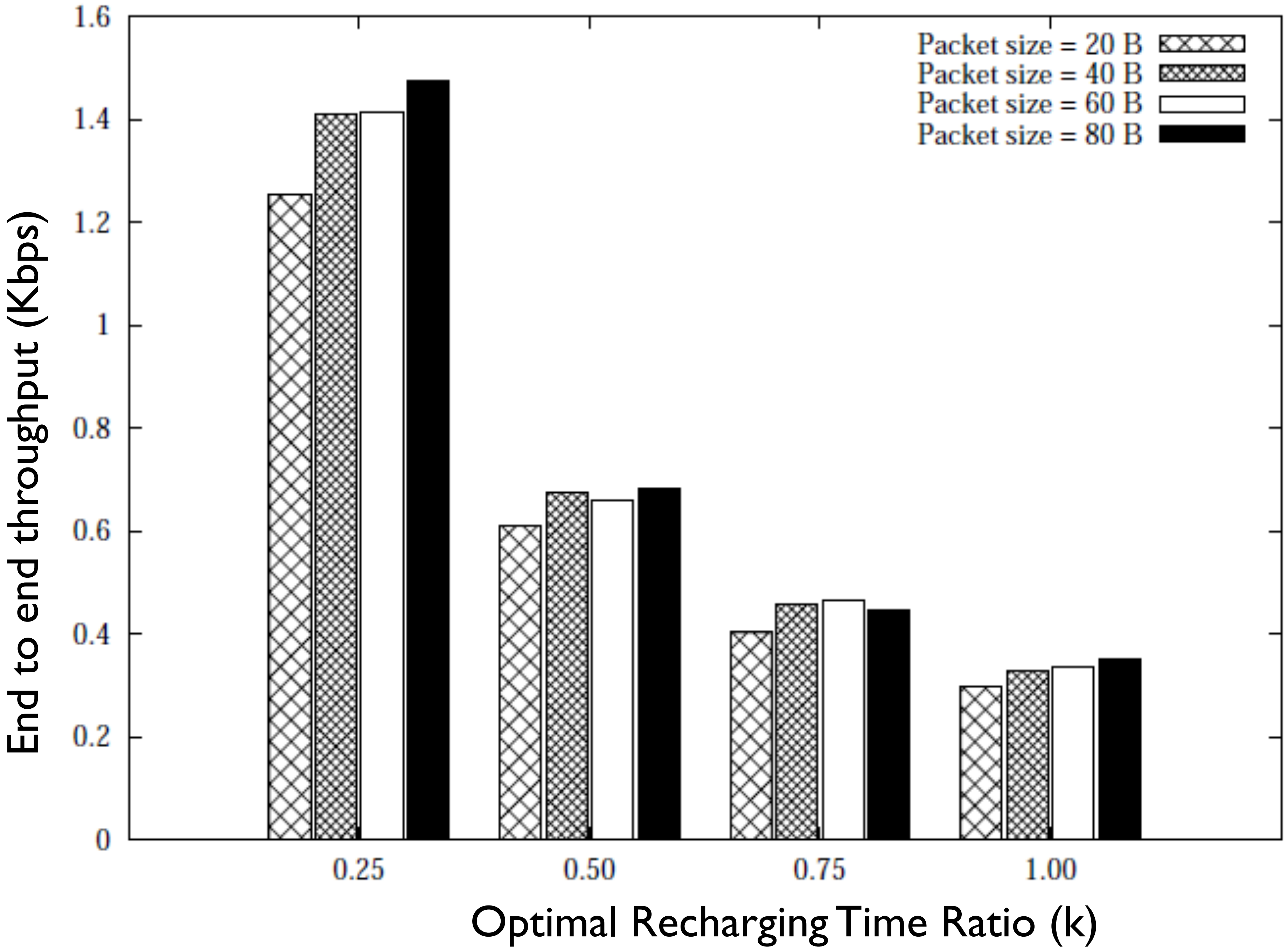
Frame time

N: total number of nodes in the path
P: Packet Data size
E_{rec} : Energy Harvesting Rate
E_{idle} : Idle Energy Consumption Rate
E_{tx} : Tx/Rx Energy Consumption Rate

Performance Evaluation

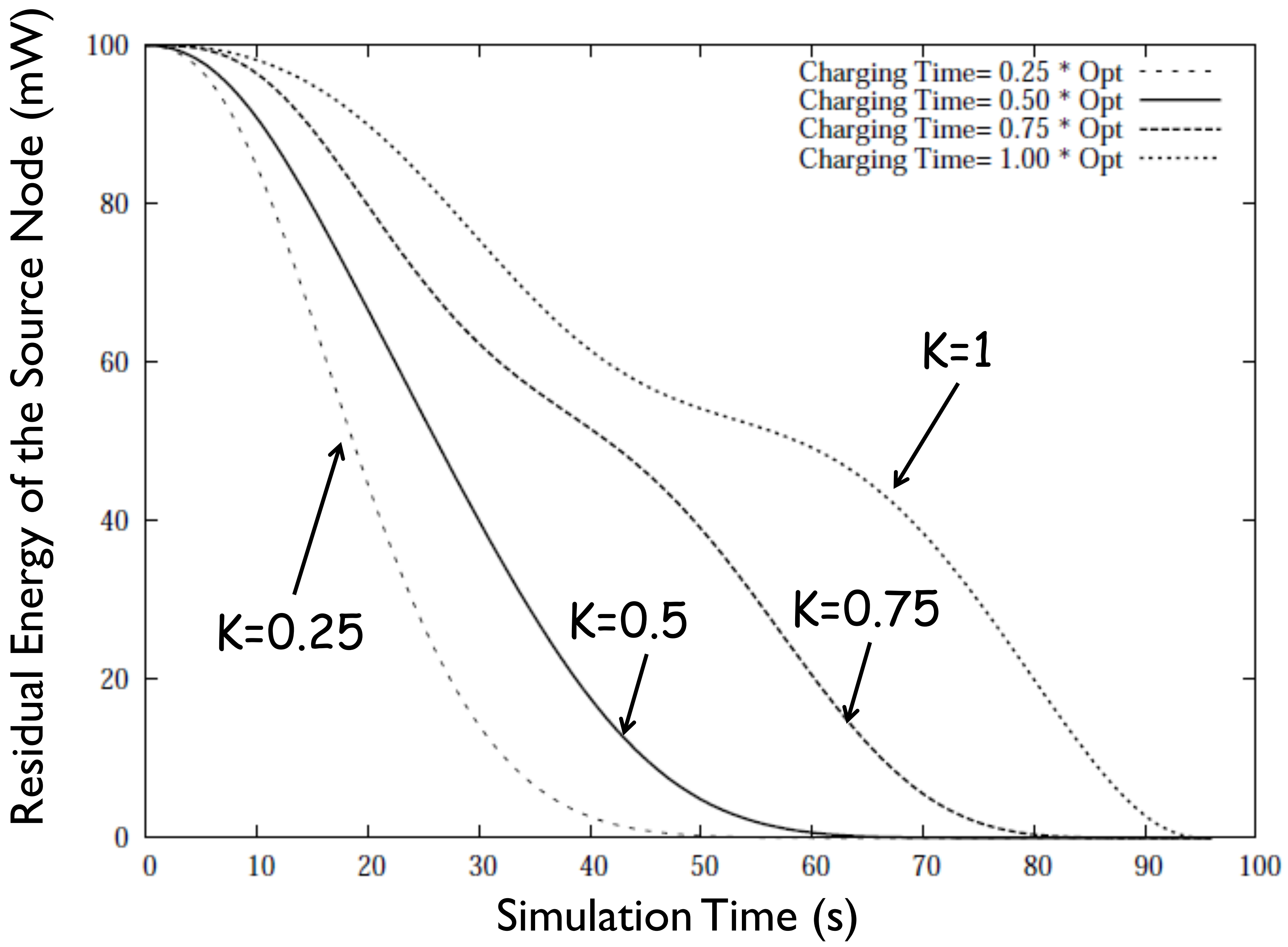
Parameter Name	**Parameter Value**
Area of simulation	300m x 300m
Number of Nodes	500, placed randomly
Number of Energy Transmitters	256, placed in 16x20 grid
Sensor Model	Mica-2 mote
Tx Power	82.23 mW
Rx Power	45.35 mW
Idle Power	17.23 mW
Tx Rate	38.4 Kbps
ESR_0	0.3
ESR_{lim}	300
Protocol Evaluations	➢ *Packet size variation, 20-80 Bytes* ➢ *Charging time variation wrt optimal value* ➢ *Average End-to-End Throughput* ➢ *Average Network Lifetime* ➢ *Residual Energy at Source Node*

Performance Evaluation



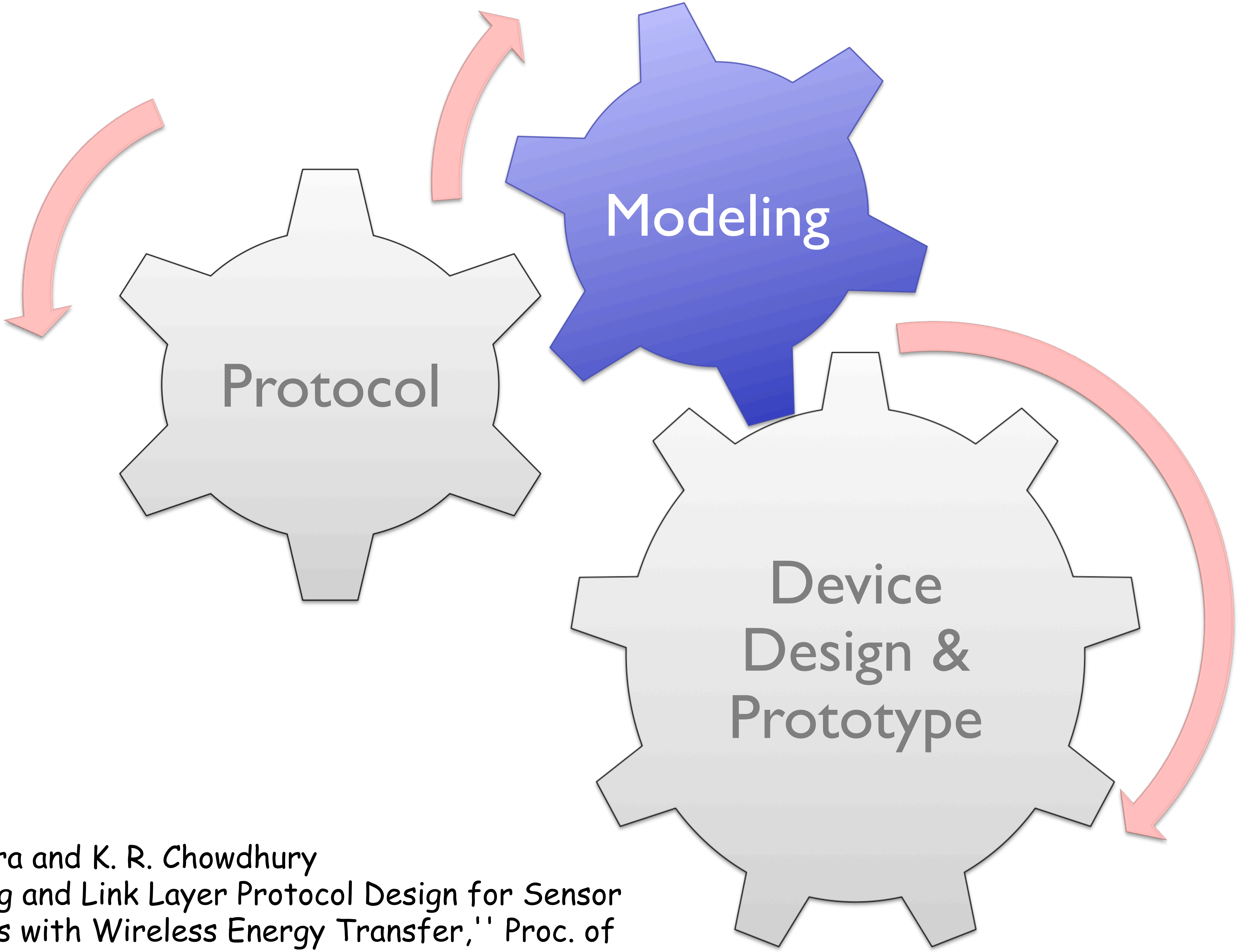
The end-to-end throughput for different packet sizes measured against increasing charging time ratio

Performance Evaluation



Residual energy at the source node as a function of simulation time

Topics



Modeling

Protocol

Device Design & Prototype

J. Ventura and K. R. Chowdhury
``Routing and Link Layer Protocol Design for Sensor Networks with Wireless Energy Transfer,'' Proc. of IEEE PIMRC, Toronto, September 2011

Energy Harvesting: Objectives

Problem?

Lack of theoretical models that map energy harvesting conditions with sensor operations, and aid in protocol design

Solution!

Develop a Markov model for capturing the energy states of the sensors equipped with multiple energy harvesting boards

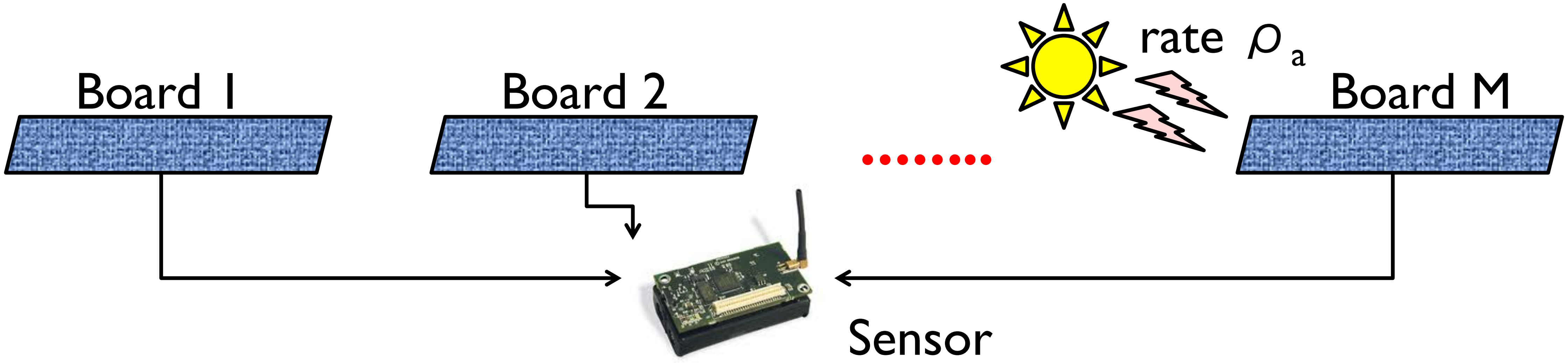
Provide simplified analytical estimation for predicting the probability of running out of energy (mis-detecting the event)

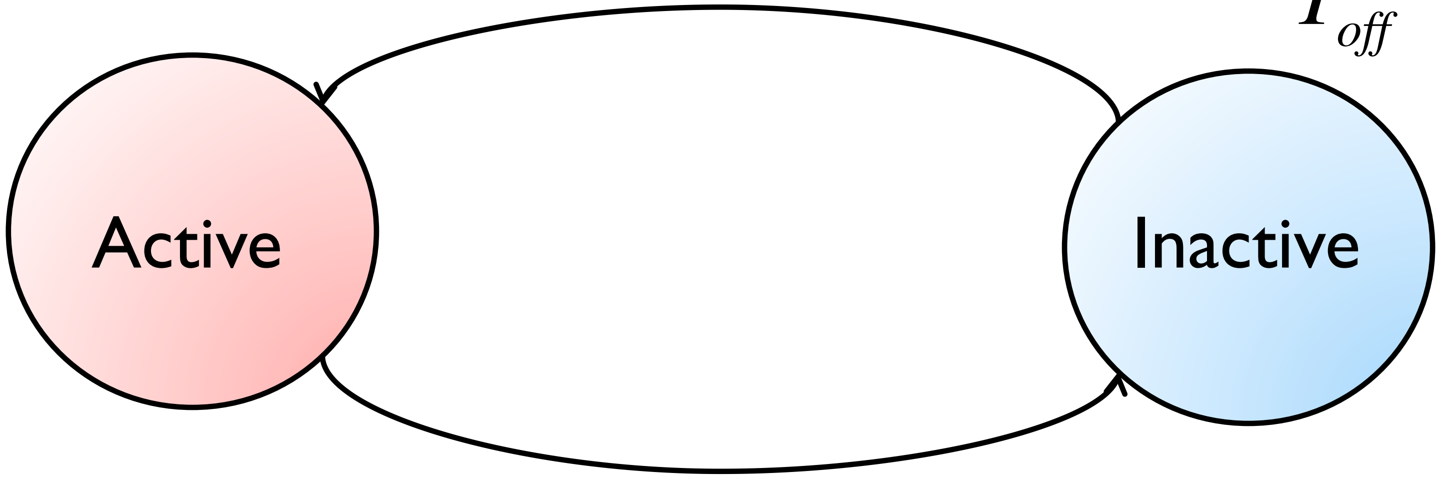
[1] A. Seyedi and B. Sikdar. ”Modeling and Analysis of Energy Harvesting Nodes in Wireless Sensor Networks,” in *Forty-Sixth Annual Allerton Conference*, Sep. 2008.

[2] S. Zhang, and A. Seyedi, ”Analysis and Design of Energy Harvesting Wireless Sensor Networks with Linear Topology”, to appear in *Proc. IEEE ICC 2011*, Jun. 2011.

Model Basics: Variables, Problem Setup

Start by assuming M boards harvesting same energy type (will be generalized later)





w: Probability to change from inactive to active $w \approx \frac{T}{T_{off}}$

T_{on}: Mean on time

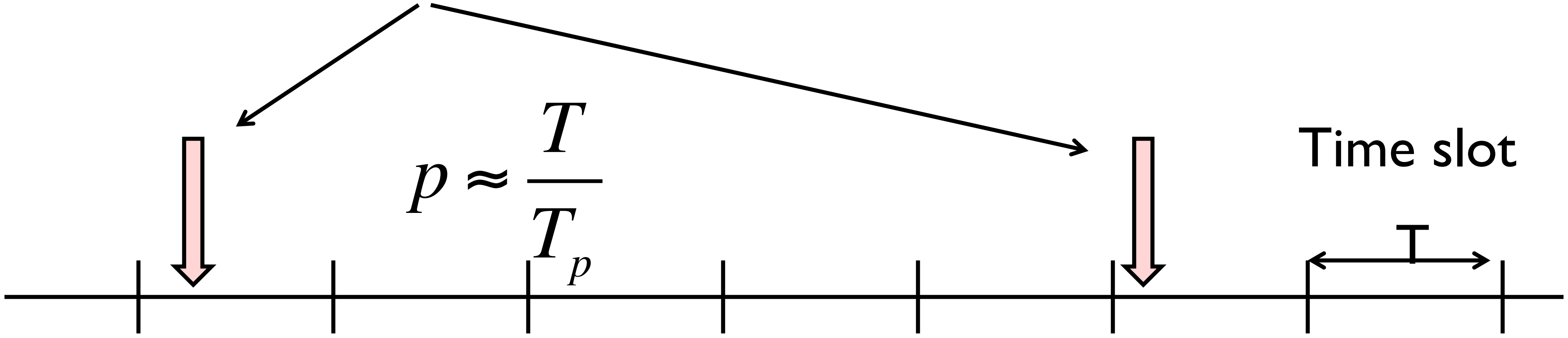
T_{off}: Mean off time

r: Probability to change from active to inactive $r \approx \frac{T}{T_{on}}$

μ=w/(w+r) : Probability to be active

Model Basics: Variables, Problem Setup

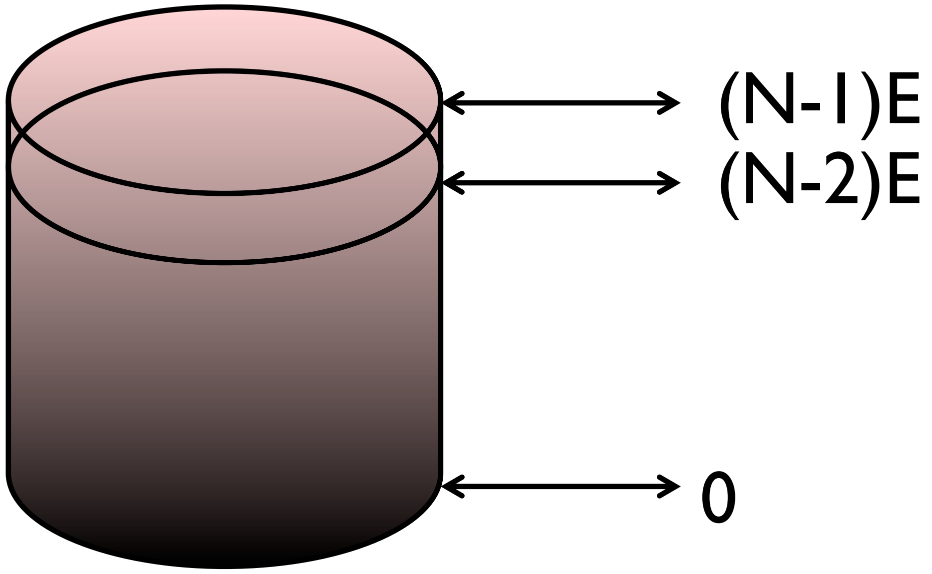
Event intervals are exponentially distributed with mean T_p and probability p



$$p \approx \frac{T}{T_p}$$

k=E/(ρ_aT) : Number of slots needed to run an event requiring energy E

Max. battery size, number of events



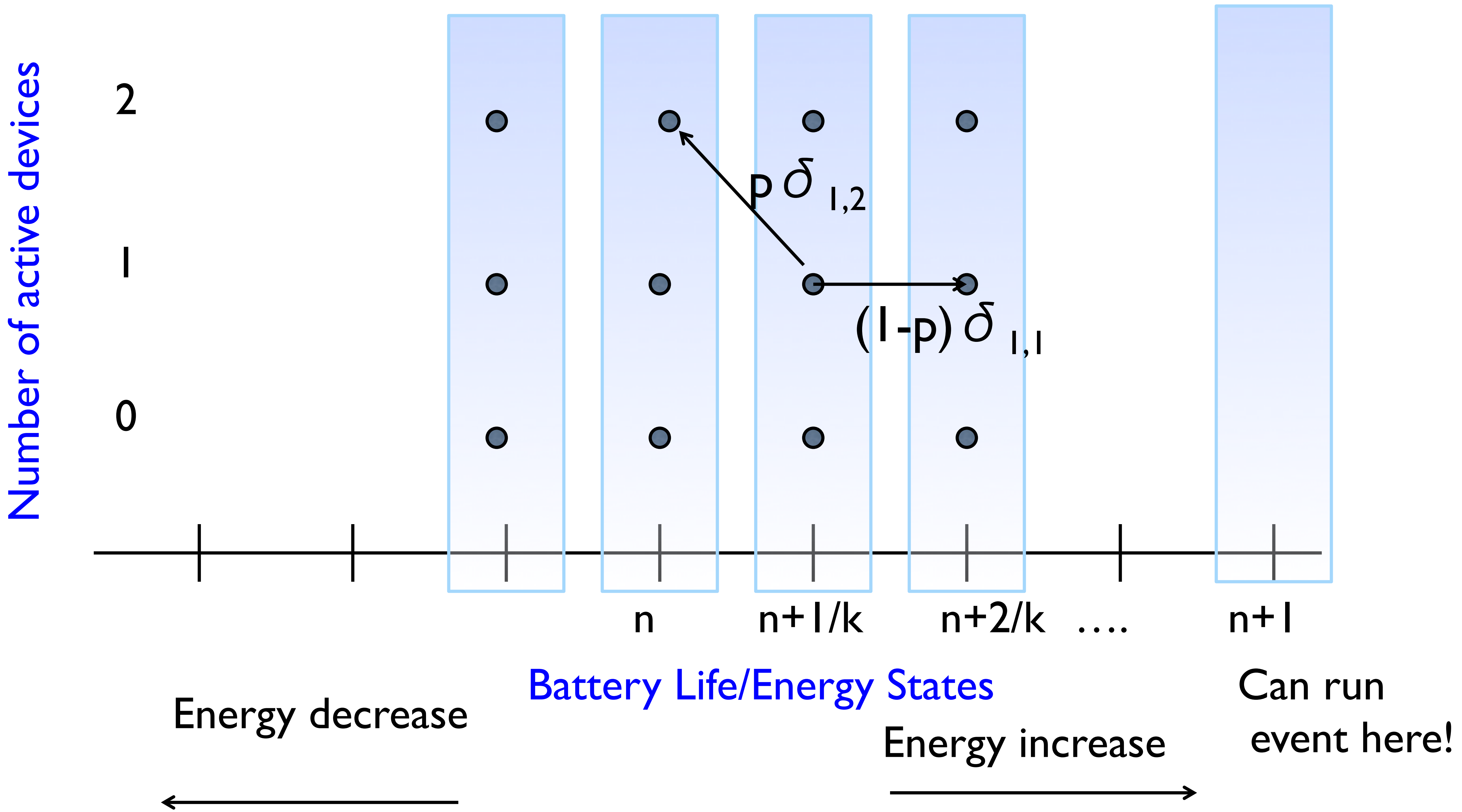
i.e., Energy required to run an event =E

Storage capacitor

Note: The energy that is being harvested during the current time slot can not be used to run an event that happens in it

MAKERS Model : General Model

MAKERS (Multiple boArd marKov model for Energy haRvesting Sensors)



Battery Life/Energy States

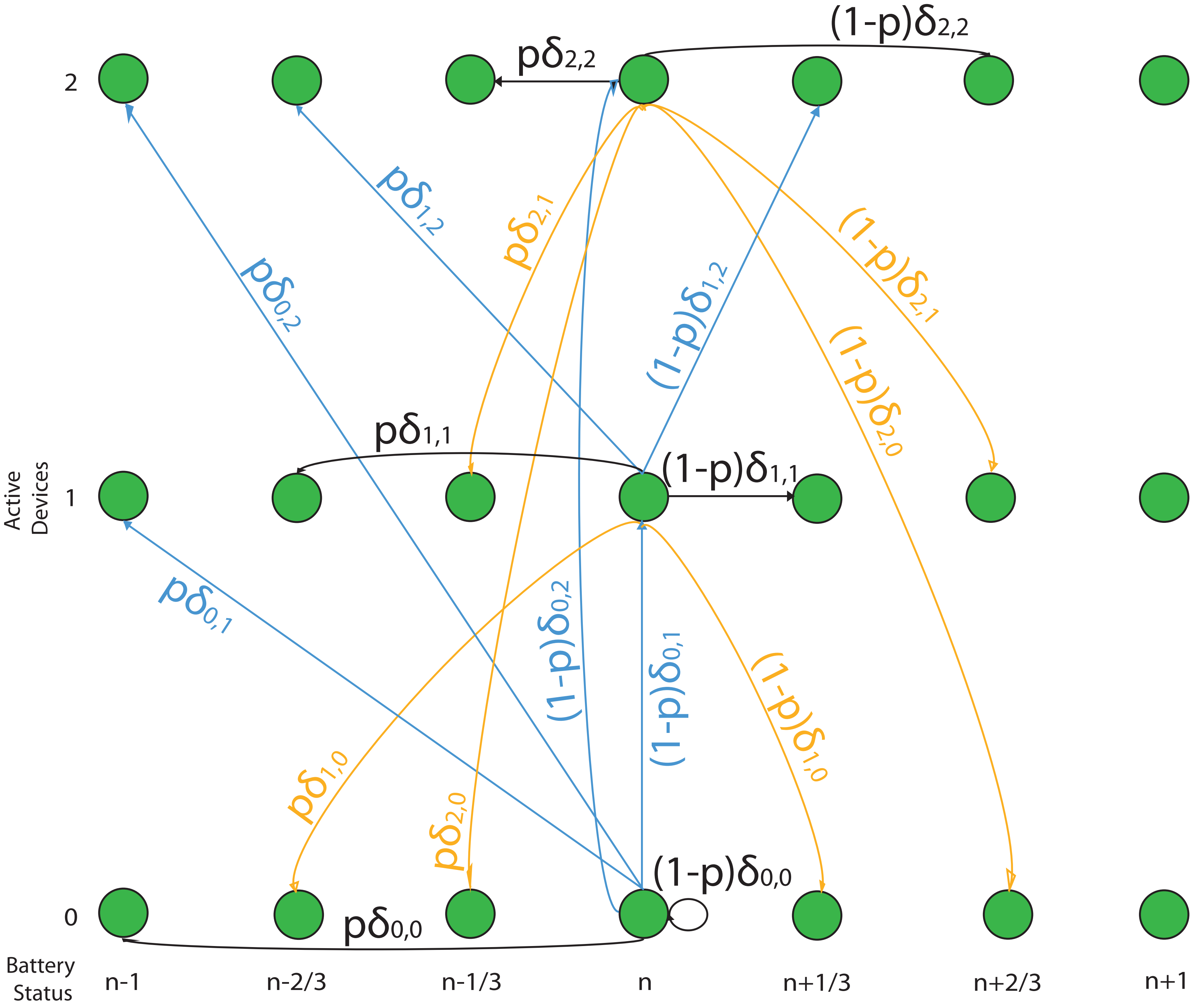
Energy decrease

Energy increase

Can run event here!

$\delta_{i,j}$: Probability of j harvesters active in the future state if i harvesters are active in the current one.

MAKERS Model : General Model



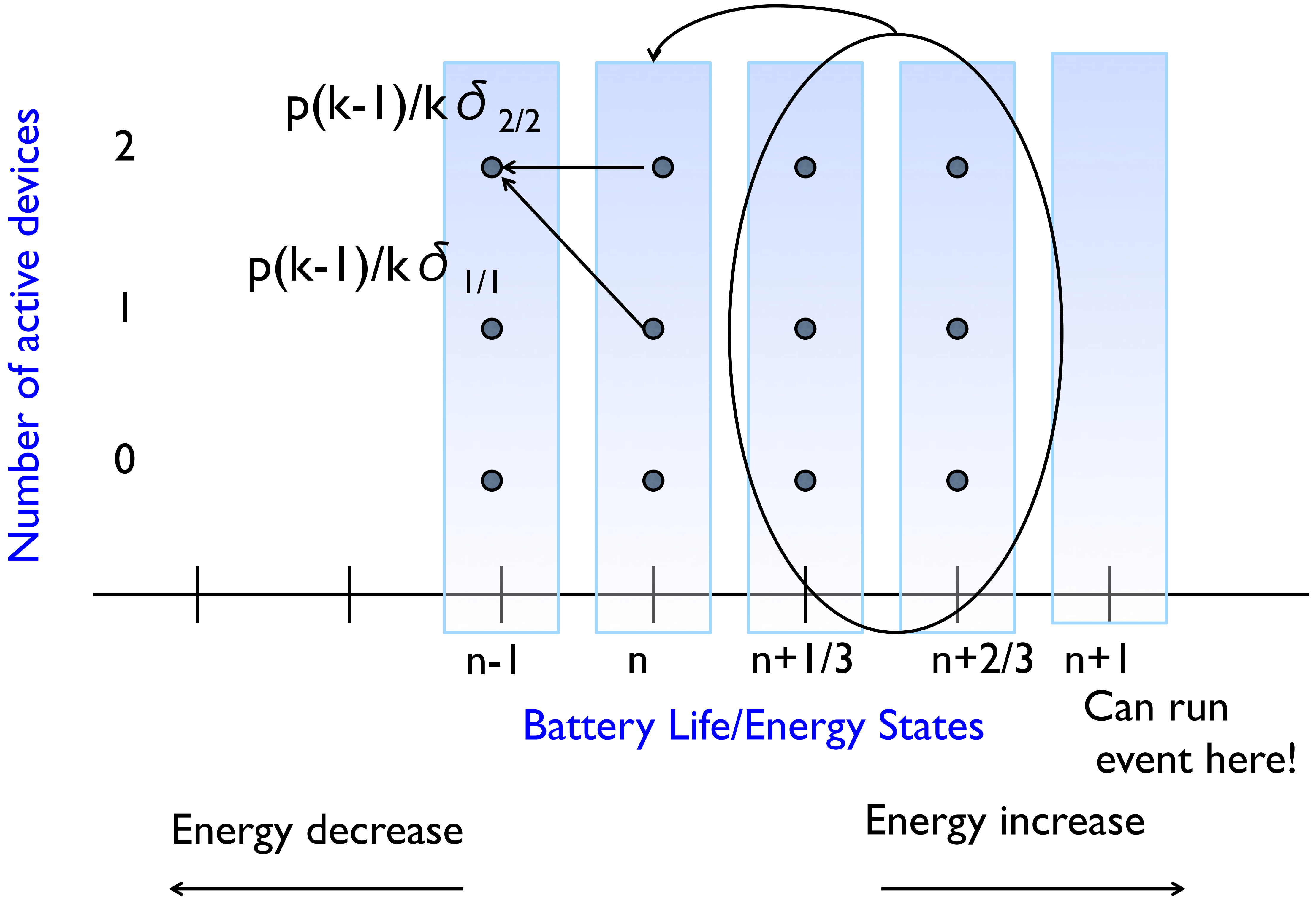
Example :

M (number of active devices)=2

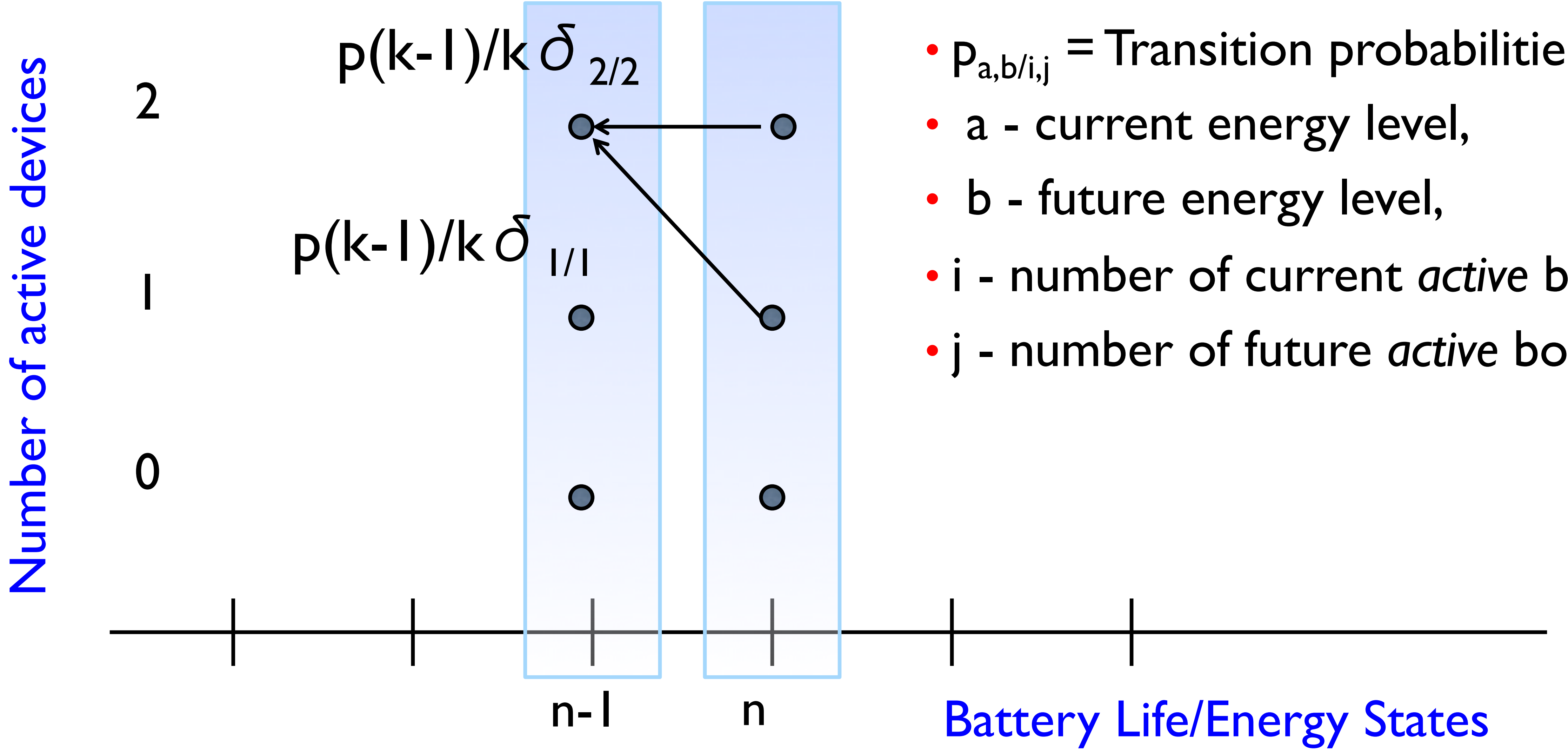
k (battery states)=3

MAKERS Model : Simplifications- Collapse Energy States

Simplification to MAKERS model: Merge intermediate battery states



MAKERS Model : Simplifications- Collapse Energy States



- $p_{a,b/i,j}$ = Transition probabilities
- a - current energy level,
- b - future energy level,
- i - number of current *active* boards
- j - number of future *active* boards

$$p_{n,n-1/i,j} = p \quad \frac{k-i}{k} \quad \delta_{i,j}$$

Prob. event occured

Prob. of residual energy less than required

Prob. i harvesters active now, j will be active next slot

Similarly, expressions derived for $p_{n,n/i,j}$ and $p_{n,n+1/i,j}$

MAKERS Model : Event Loss Probability

Event Loss: Occurs when sensor does not have stored energy E to process an event

$$P_L = \begin{cases} \frac{(1-p)(1-\gamma)}{1-\gamma^N-p(1-\gamma)} & (1-p)\alpha < p(1-\alpha) \\ \frac{1}{1+\frac{1}{1-p}\sum_{n=1}^{N-1}\gamma^n} & (1-p)\alpha > p(1-\alpha) \end{cases}$$

$$\alpha = \sum_{i=0}^{M} \frac{i}{k}\phi_i$$

Total residual energy averaging for "i" active harvesters

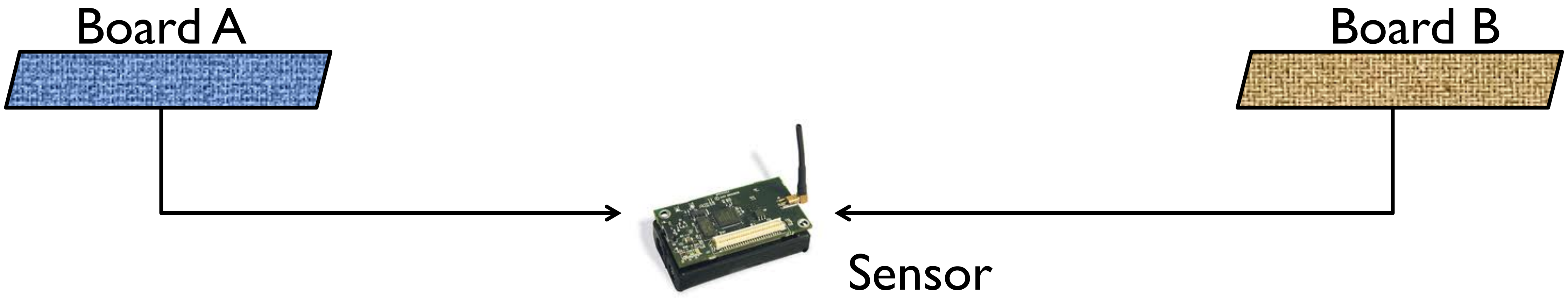
$$\phi_i$$

Binomial distribution of choosing "i" active devices

$$\gamma = \frac{(1-p)\alpha}{p(1-\alpha)}$$

MAKERS Model : Multiple Boards/Energy Sources

Consider two boards:



Board A

Board B

Sensor

$$\rho_A, r_A, w_A, \mu_A = \frac{w_A}{r_A + w_A}$$

$$\rho_B, r_B, w_B, \mu_B = \frac{w_B}{r_B + w_B}$$

Assumption: Let b be a real positive number, b+1<k

$$\boxed{\rho_B = b\rho_A}$$

Harvesting rates are different!

MAKERS Model : Multiple Boards/Energy Sources

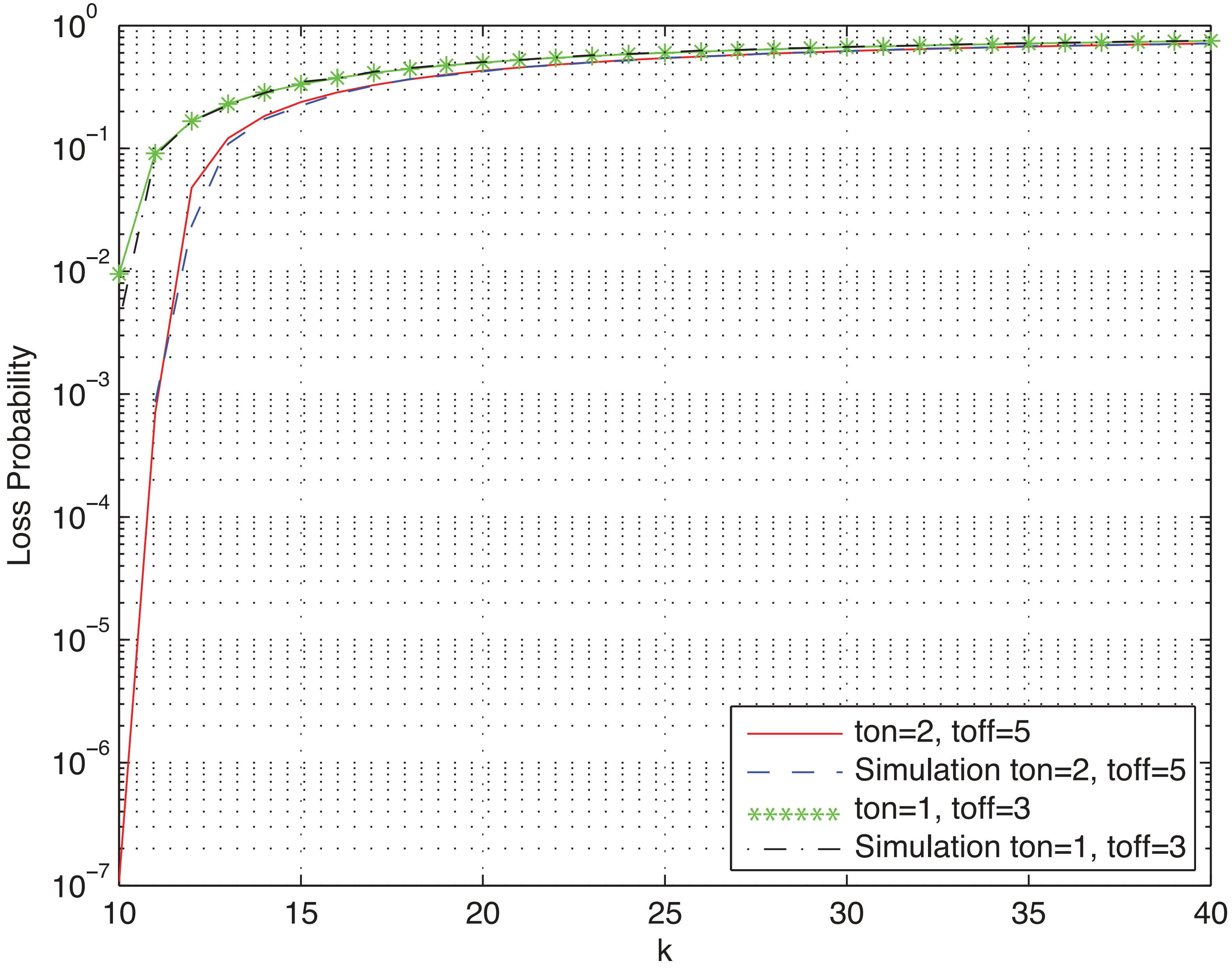
New formulation for total residual energy:

$$\alpha = \frac{1}{k}\mu_A(1-\mu_B) + \frac{b}{k}\mu_B(1-\mu_A) + \frac{b+1}{k}\mu_A\mu_B$$

Only board A is active   Only board B is active   Both boards are active

Can be trivially extended for n different boards with different harvesting rates

Results



Loss Probability vs k for N=100, M=2, p=0.05

- Monte-Carlo continuous-time simulations are undertaken in MATLAB to evaluate our approach

Thank You