DEPARTMENT OF
INFORMATION
ENGINEERING
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System Designs for Energy Harvesting Sensor Networks [1]

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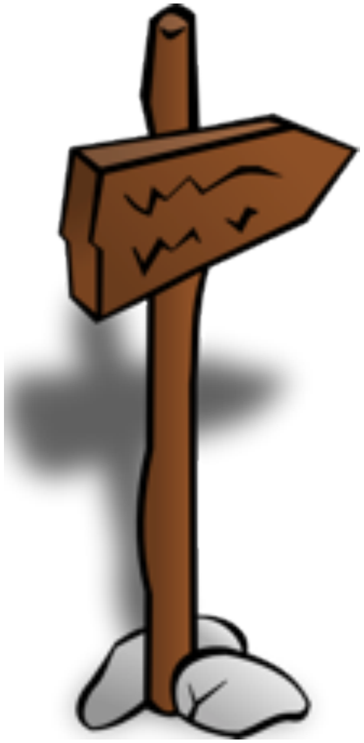
Outline

- Motivation
- Reference scenario
- Energy source model
- System model
  - Network, MAC, consumption
- Stochastic optimization
- Results



Motivation

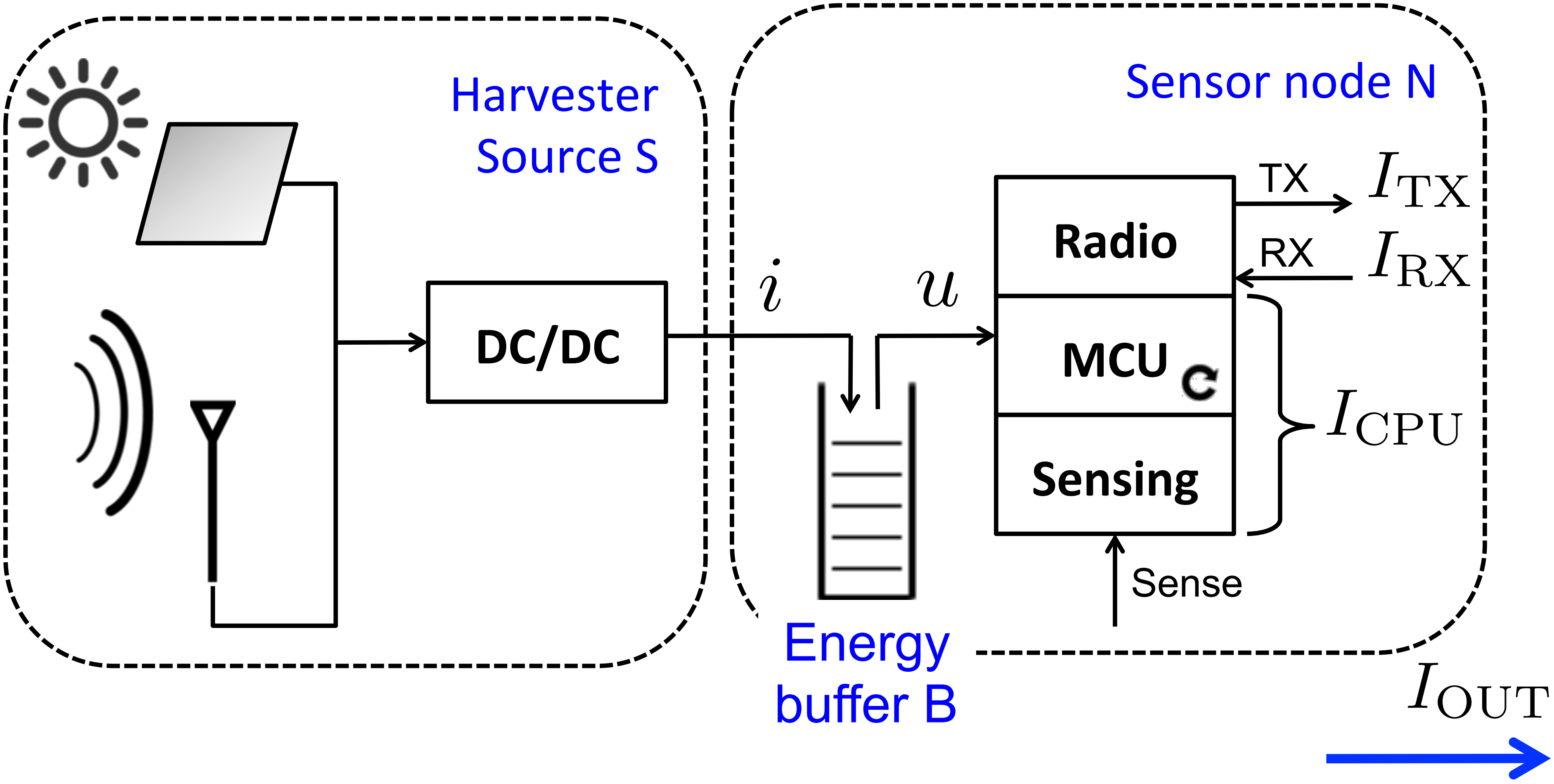
- Is there any free lunch for EH WSNs?
- Challenge:

  Energy source is there but …

  … it is unreliable, erratic and intermittent
- Need for intelligent designs
  - Adaptive energy mangement
  - Transmission *vs* Storage *vs* Scavenger Size

Reference Scenario (1/2)

Sensor Model



Reference Scenario (2/2)

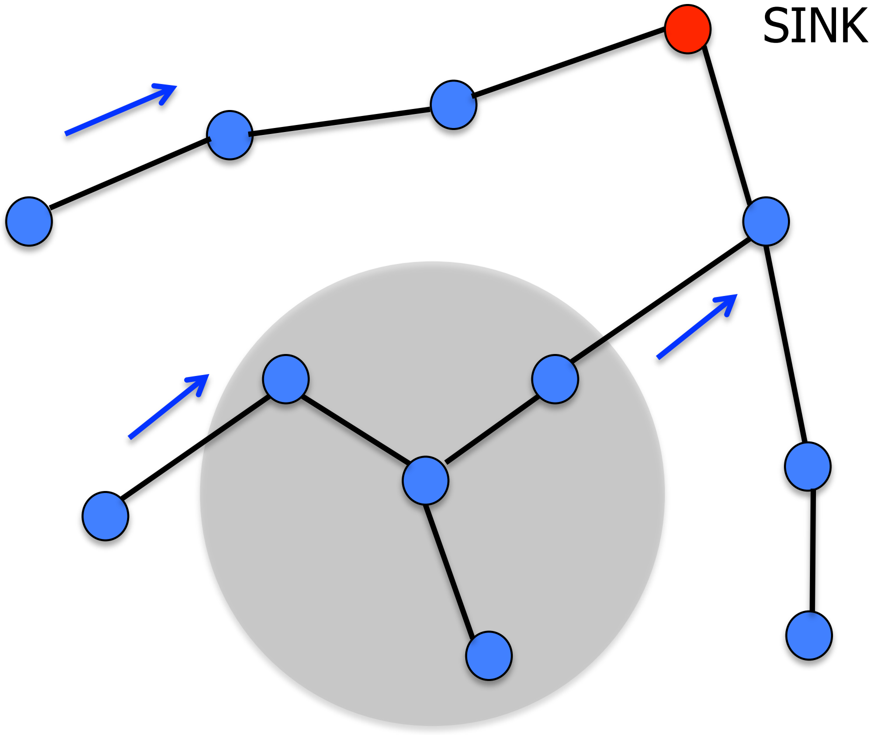
Network Model

Scenario

- Multi-hop routing
- Data collection @ the sink
- Energy harvesting nodes

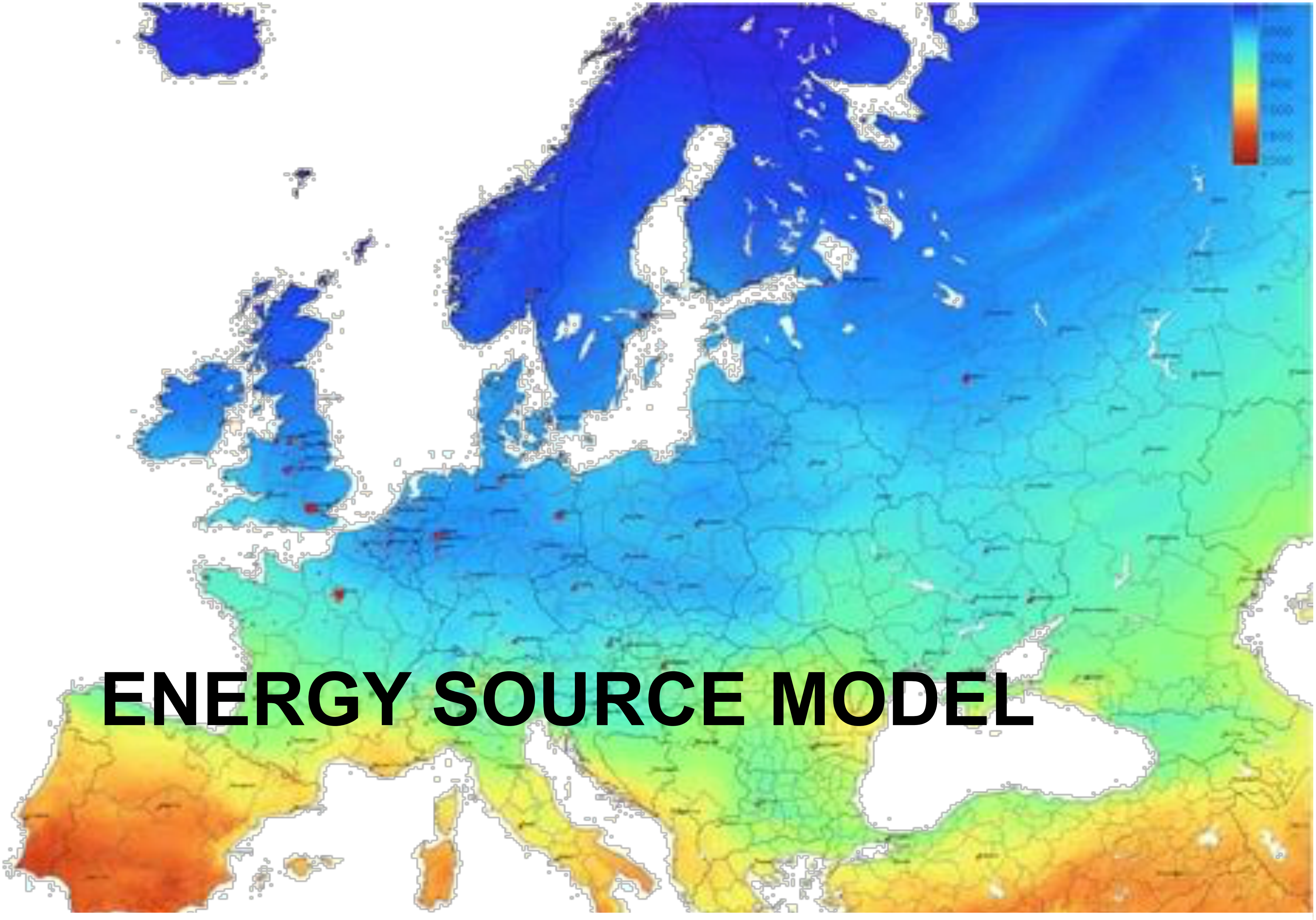
Aspects to model

- MAC (channel access)
- Routing
- Energy consumption
- Energy arrival

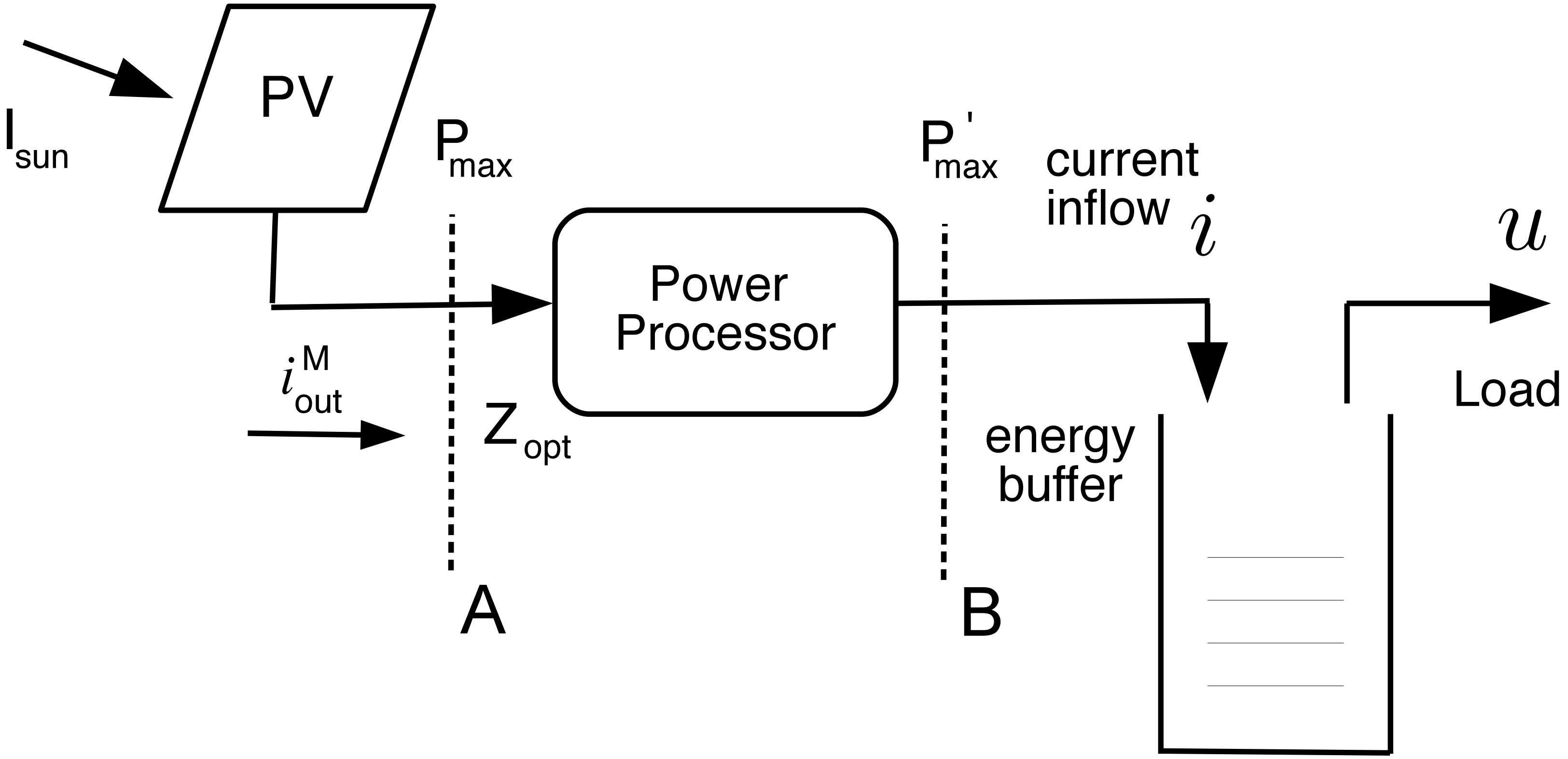


coverage range
(node density)

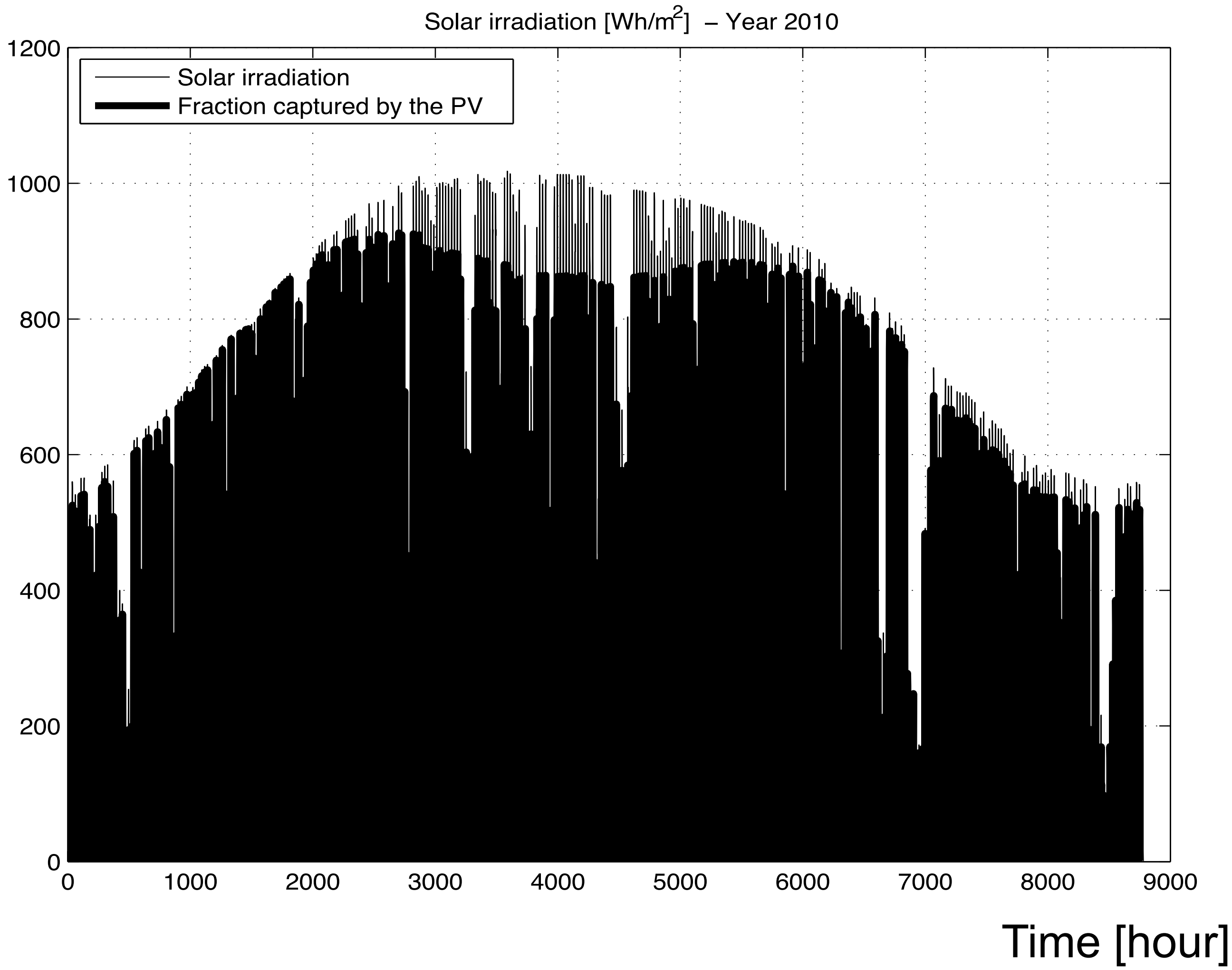
ENERGY SOURCE MODEL



Energy Source Model



Solar Radiation Maps



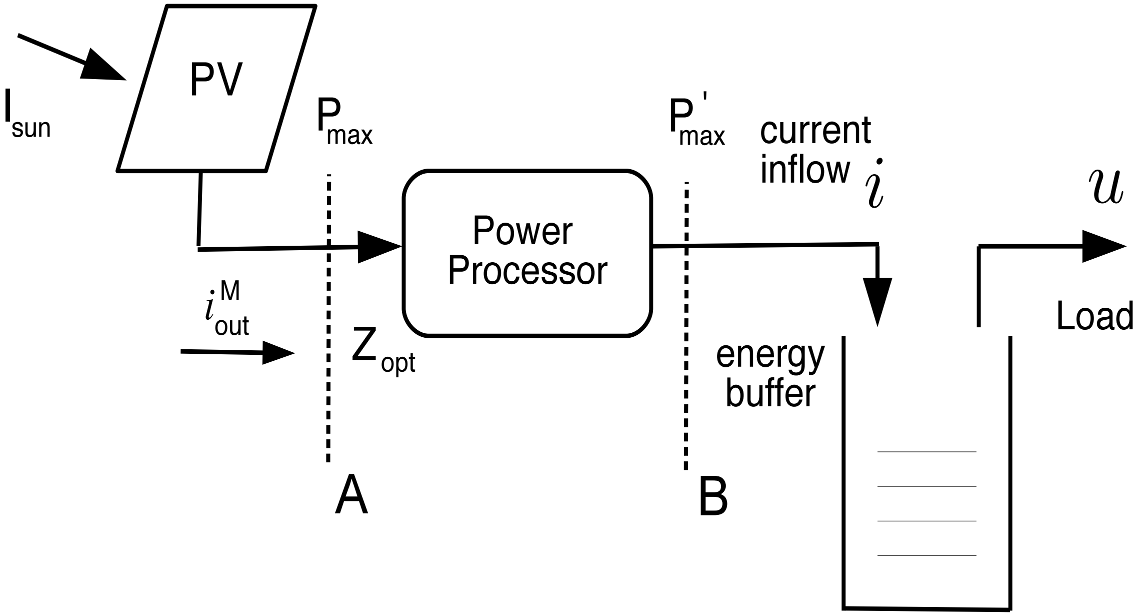
Example

Solar Irradiation for
Los Angeles in 2010

From NREL:
http://www.nrel.gov/rredc/

NREL, National Renewable Energy Laboratory, “Renewable Resource Data Center,” http://www.nrel.gov/rredc/

Harvested energy [2]



Solar radiation maps:

- Latitude, longitude
- Orientation, tilt of the panel
- Day of year

PV technology:

- Material
- Efficiency
- Panel size

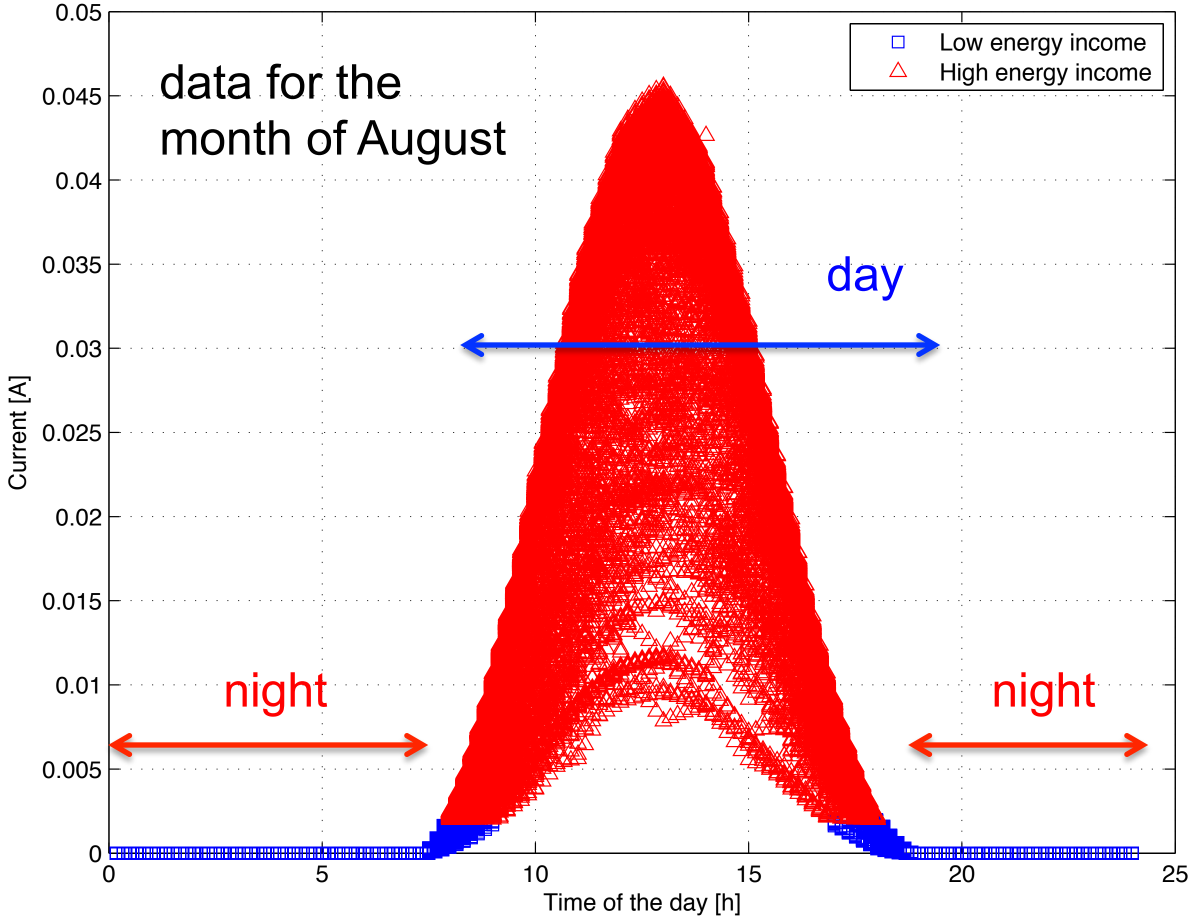
DC/DC:

- Efficiency
- Optimal working point for the panel IV curve is assumed

Statistical characterization of DC/DC out current

- Current intensity [A]
- Energy states (morning, afternoon, night, etc.)

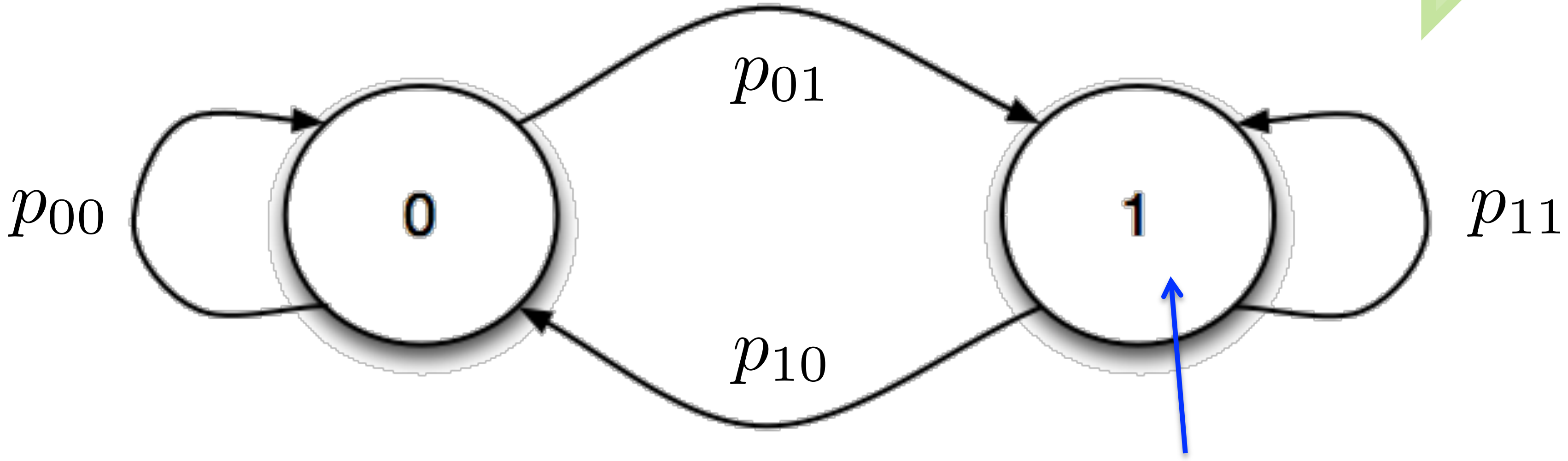
Example



Statistics (pdf)

- LA – August 1999-2010
- Day/Night data clustering
- Duration of "energy states"
- Current income in each

Semi-Markov Model (SMM)



$f_c(i|x_s)$ harvested current

$f_d(\tau|x_s)$ permanence time

Embedded chain probs

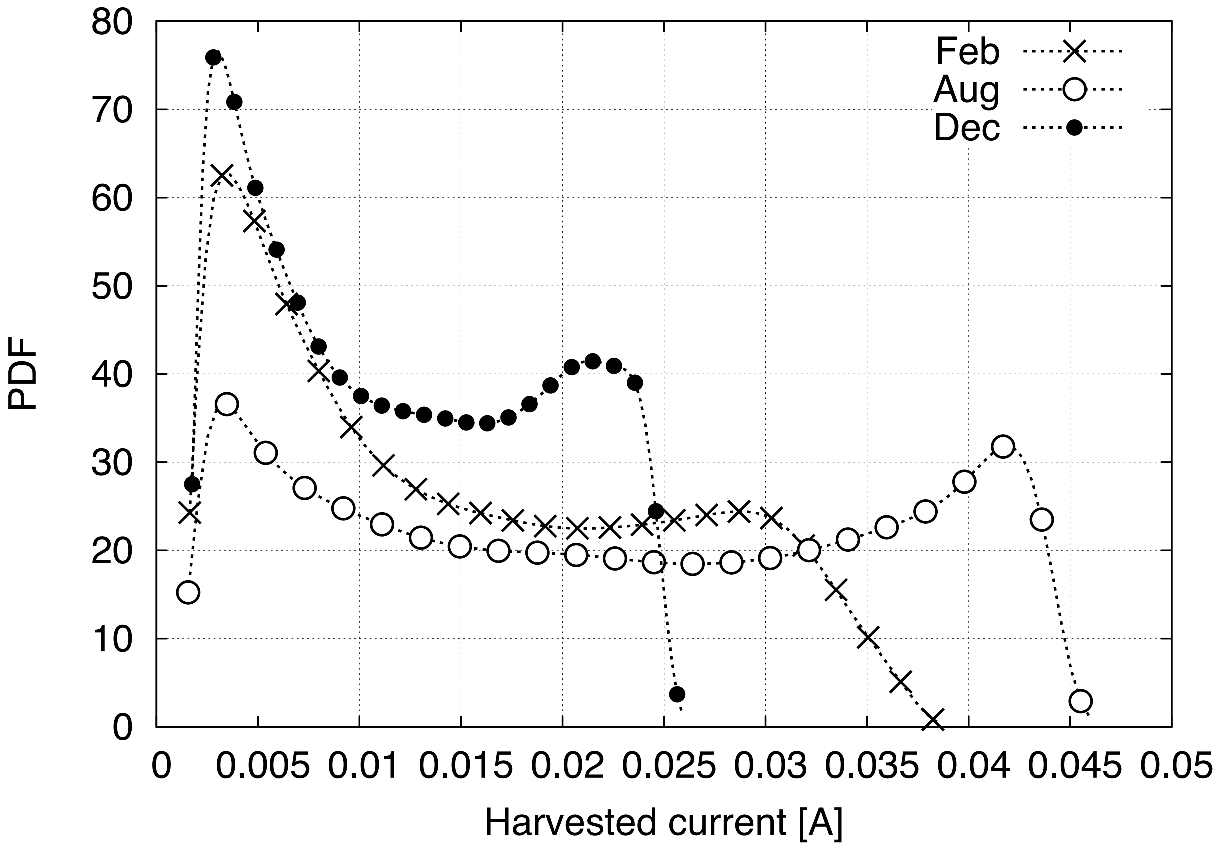
$$p_{10} = p_{01} = 1$$

$$p_{00} = p_{11} = 0$$

the approach has been generalized to any number of states

Statistics – input current $f_c(x|x_s)$

LA - from data collected in [1999-2010]

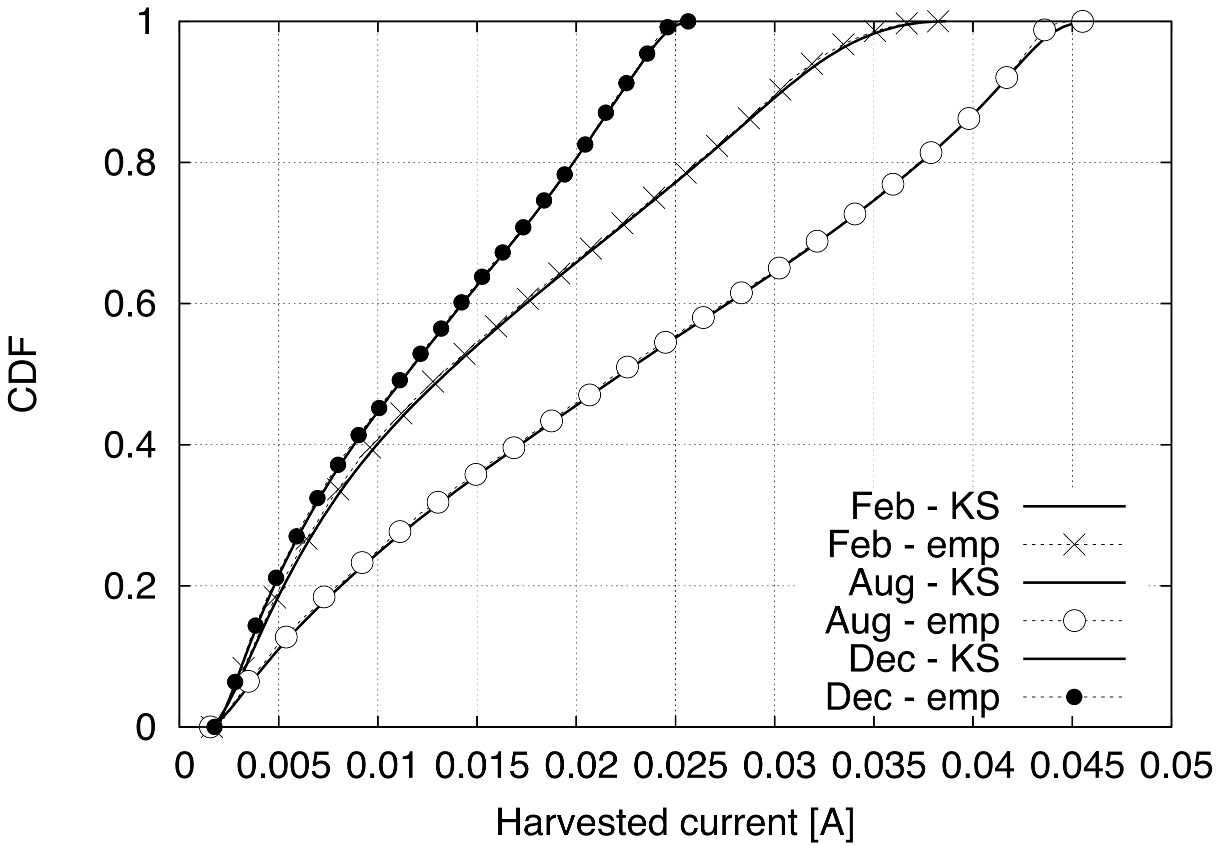


Solar module:
6x6 square-cm

State x_s= 0: day

Statistics – input current cdf

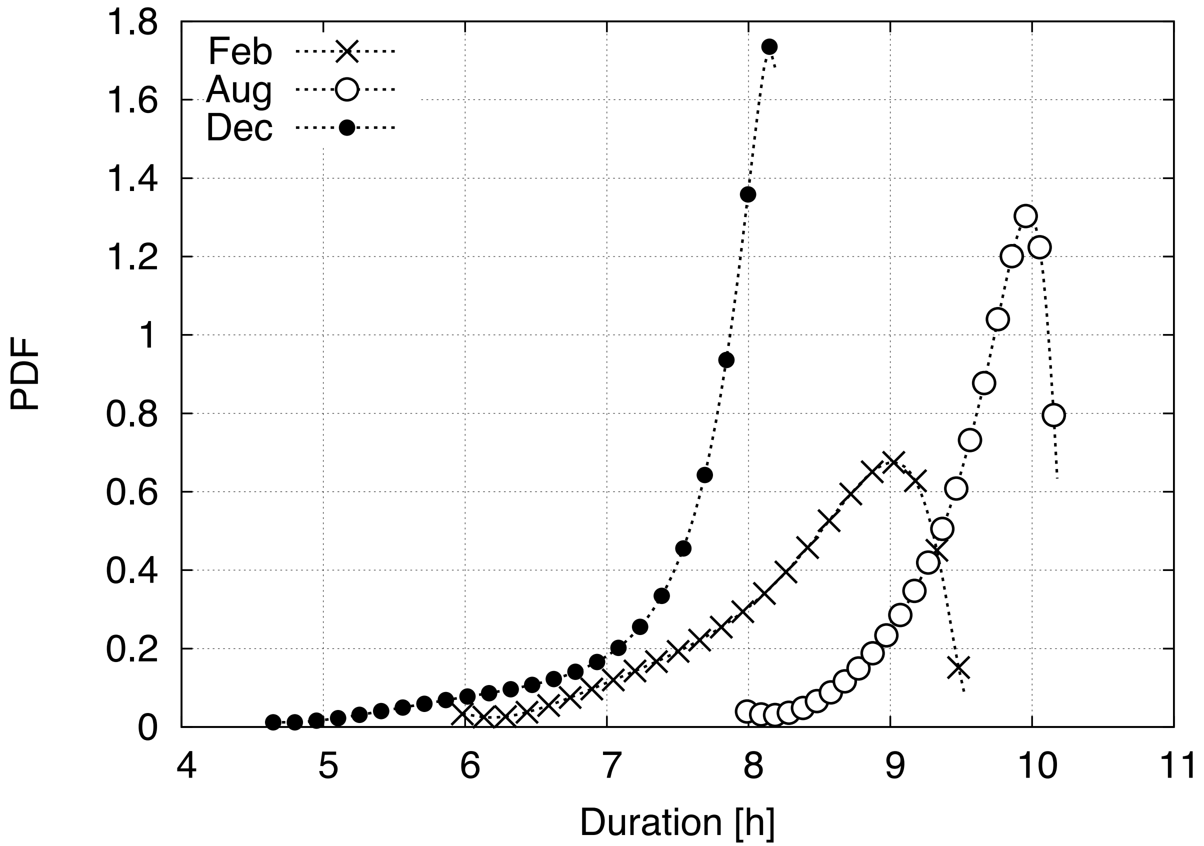
LA - from data collected in [1999-2010]



State x_s= 0: day

Statistics – duration $f_d(x|x_s)$

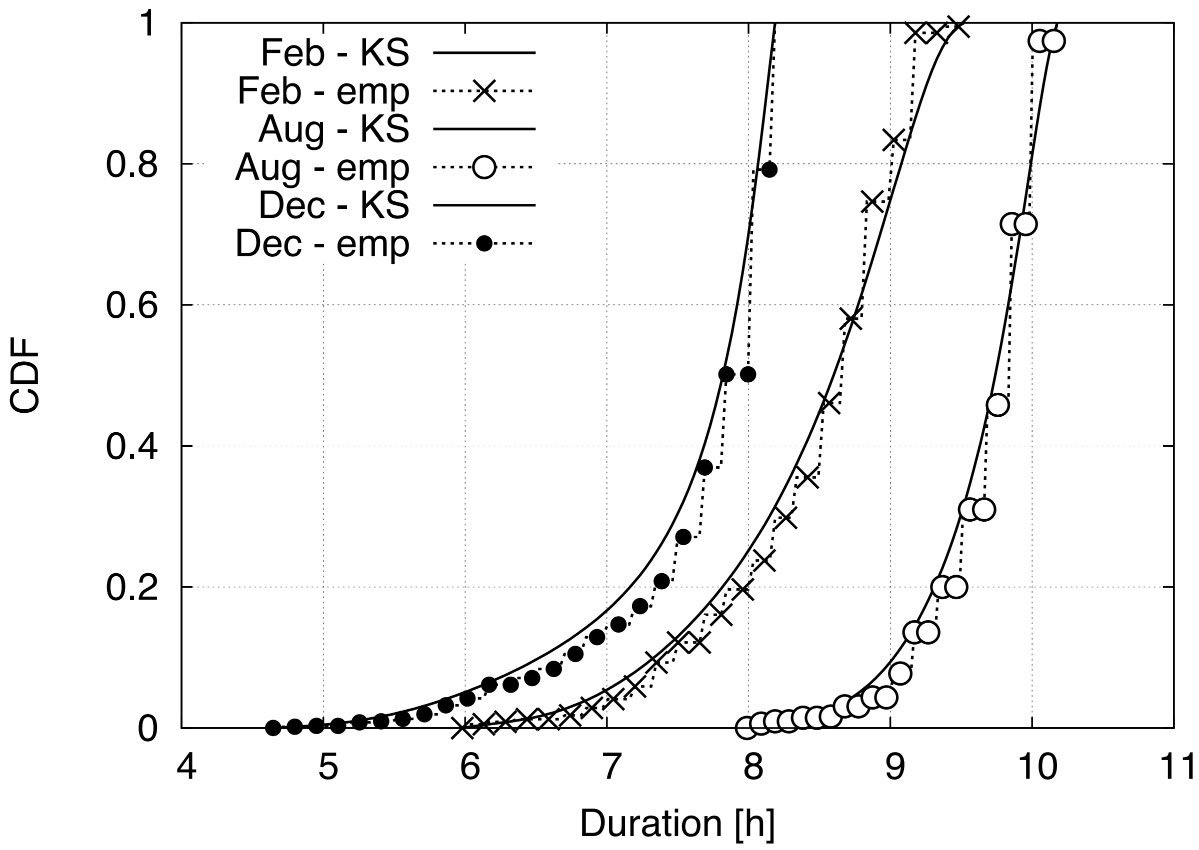
LA - from data collected in [1999-2010]



State x_s= 0: day

Statistics – duration cdf

LA - from data collected in [1999-2010]



State x_s= 0: day

Stage

Stage

- time τ during which the SMM remains in one state

Energy income

- r.v. drawn @ beginning of stage from $f_c(i|x_s)$

Duration

- r.v. drawn @ beginning of stage from $f_d(\tau|x_s)$

Decision

- u: chosen @ beginning of stage

Δ−charge (q) in stage k

Balance between

- Control u (current drained)
- Input current i (from panel)
- Stage duration τ

$$q = (i - u)\tau$$

(for a given u, q is given by the product of two r.v.s.)

The resulting pdf h(q | x_s,u) of the variation of charge in a stage is:

$$h(q|x_s, u) = \int_{-\infty}^{+\infty} \frac{1}{|\tau|} f_d(\tau|x_s) f_c(q/\tau + u|x_s) d\tau$$

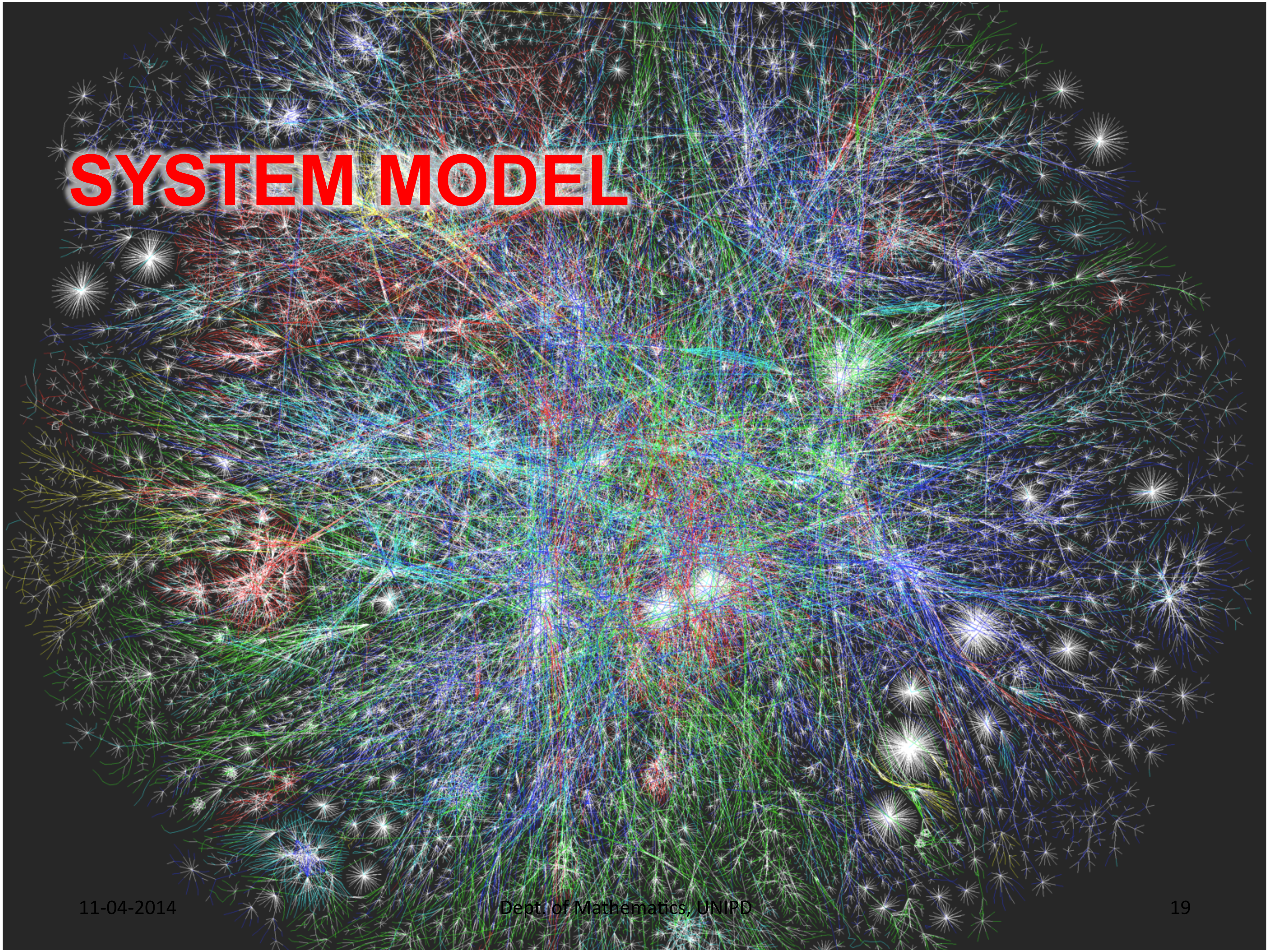
From SMM to DTMC

With $h(q \mid x_s,u)$ we

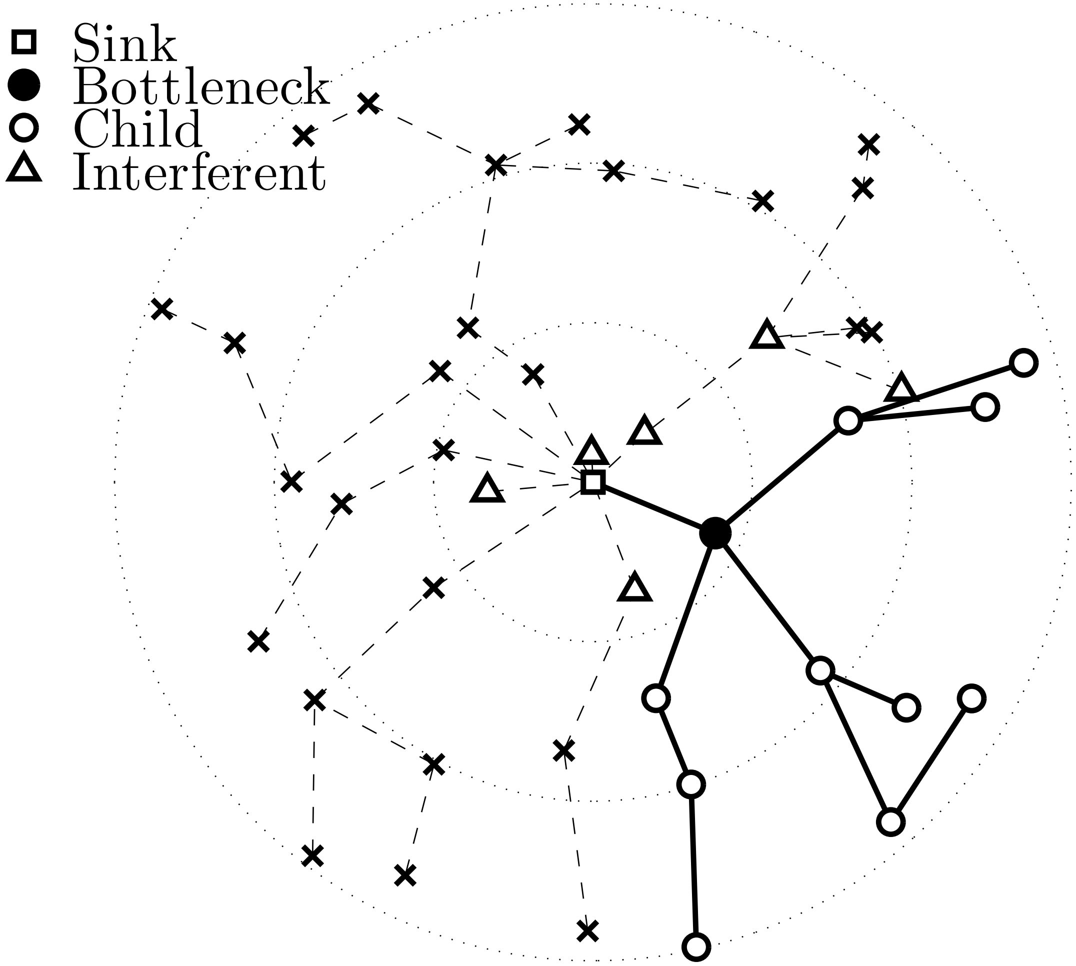
- Define an equivalent Discrete Time Markov Chain (DTMC)
- DTMC: time is slotted and slot duration is fixed
- When going from stage k-1 to stage k:
  - The resulting Δ−charge is modeled through q (pdf $h(q|x_s,u)$)
  - u is the control for the current stage k
  - x_s is the source state in the current stage k
  - q is the variation of charge in the battery:

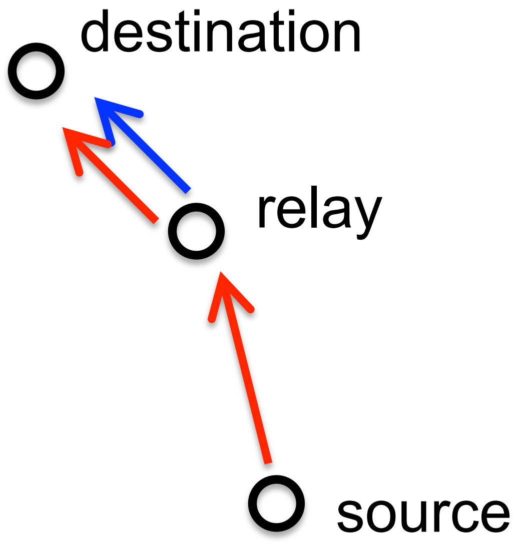
$$x_b(k) = \max\{0, \min\{x_b(k-1) + q, Q_{\max}\}\}$$

SYSTEM MODEL



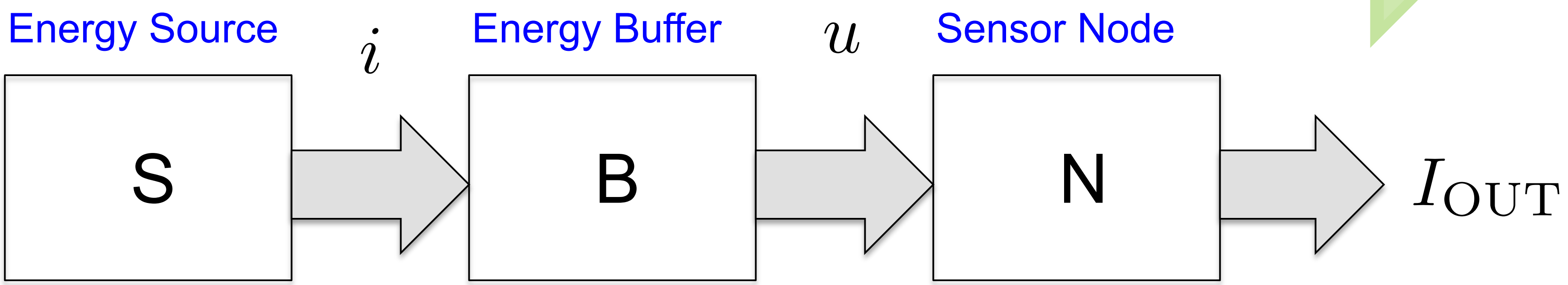
Topology, Routing & Bottleneck





own vs relayed data

Optimization Framework


Energy Source

i

Energy Buffer

u

Sensor Node

S

B

N

I_{OUT}

optimal working point for N

$$P1 : \text{maximize}\, f_{\mathrm{U}}$$
$$\text{given } I_{\mathrm{OUT}} \leq u$$

optimal energy-neutral policies

$$P2 : \text{maximize reward}$$
$$\text{given source model } S$$

We optimize for the bottleneck node N → this assures network stability

Presentation Flow

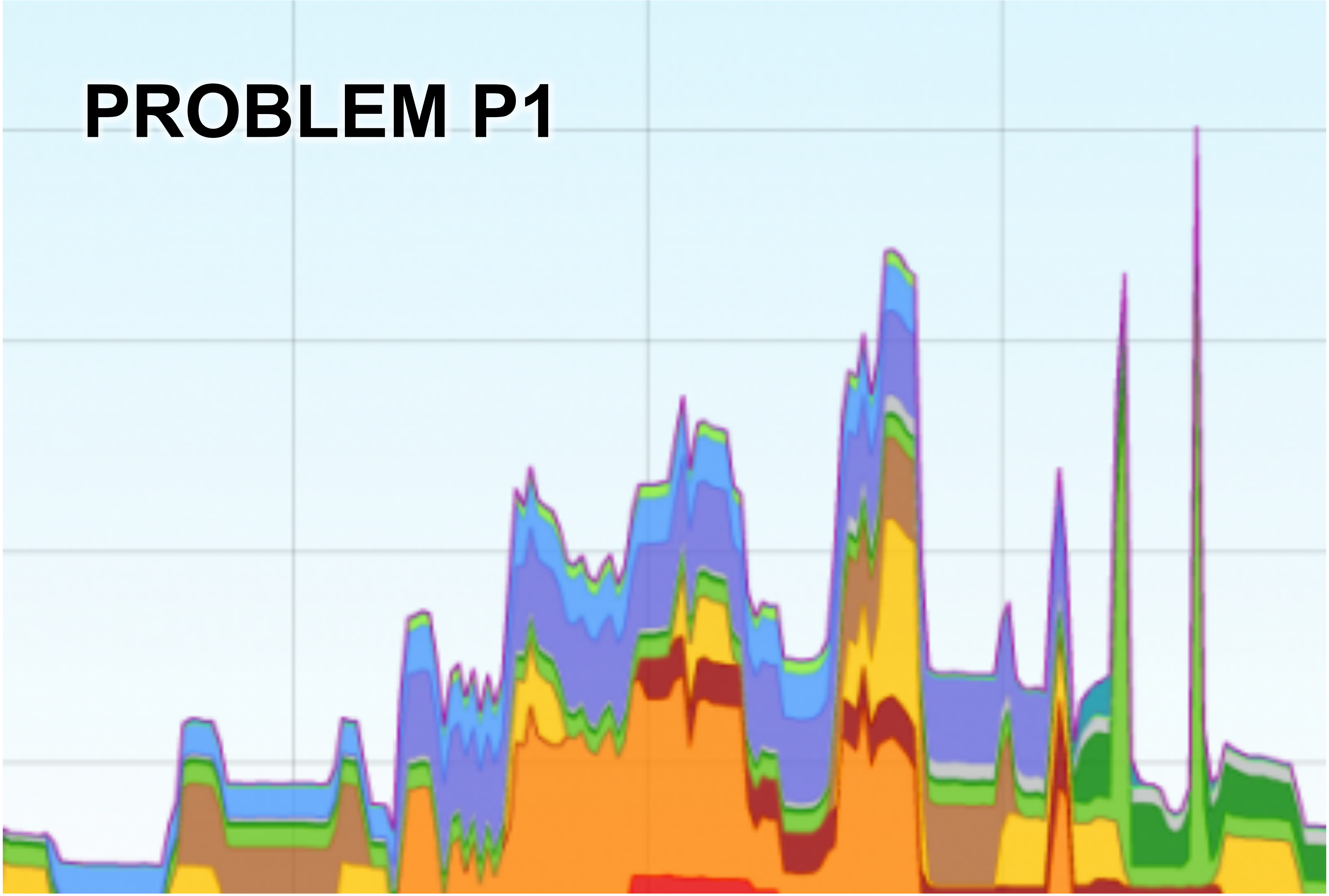
P1] optimal operational point, given u

- (inter-pkt TX time, duty cycle) $\rightarrow (t^*_{\mathrm{U}}, t^*_{\mathrm{dc}})$

P2] energetically self-sufficient policies

- Online energy management
- Optimal behavior given the solution of P1
- Results

PROBLEM P1



Energy Consumption Model

- MAC (channel access)
- Network topology
- Data gathering
- Networking
- Processing

$$I_X = i_X t_X f_X$$

Energy Consumption Model

- MAC (channel access)
- Network topology
- Data gathering
- Networking
- Processing

average time spent in state X upon a transition to that state

$$I_X = i_X t_X f_X$$

Energy Consumption Model

- MAC (channel access)
- Network topology
- Data gathering
- Networking
- Processing

average time spent …

visits per second to state X (frequency)

$$I_X = i_X t_X \boxed{f_X}$$

Energy Consumption Model

- MAC (channel access)
- Network topology
- Data gathering
- Networking
- Processing

average time spent…

visits per second…

current drawn

$$I_X = i_X t_X f_X$$

Energy Consumption Model

- MAC (channel access)
- Network topology
- Data gathering
- Networking
- Processing

average time spent…

visits per second…

current drawn

average current drained

$$\boxed{I_X} = i_X t_X f_X$$

Energy Consumption Model

Adding up the contributions from all states

$$I_X = i_X t_X f_X$$

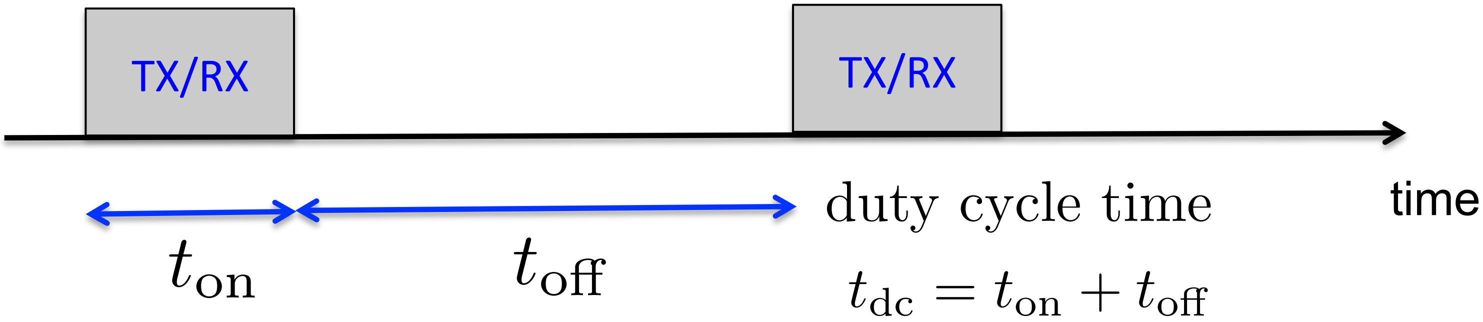
Average amount of current drained in state X

$$r_X = t_X f_X$$

Fraction of time spent in state X

$$\begin{aligned} I_{\mathrm{OUT}} &= \sum_{i \in \mathcal{X}} I_i \\ &= I_{\mathrm{TX}} + I_{\mathrm{RX}} + I_{\mathrm{INT}} + I_{\mathrm{CPU}} + I_{\mathrm{IDLE-ON}} + I_{\mathrm{IDLE-OFF}} \end{aligned}$$

MAC: duty-cycled WSN



- Energy consumption in TX, RX and IDLE is comparable
- Energy consumption is dominated by the PHY (radio)
- Commonly nodes are operated according to a duty-cycled approach
- The duty cycle d [%] is defined as:

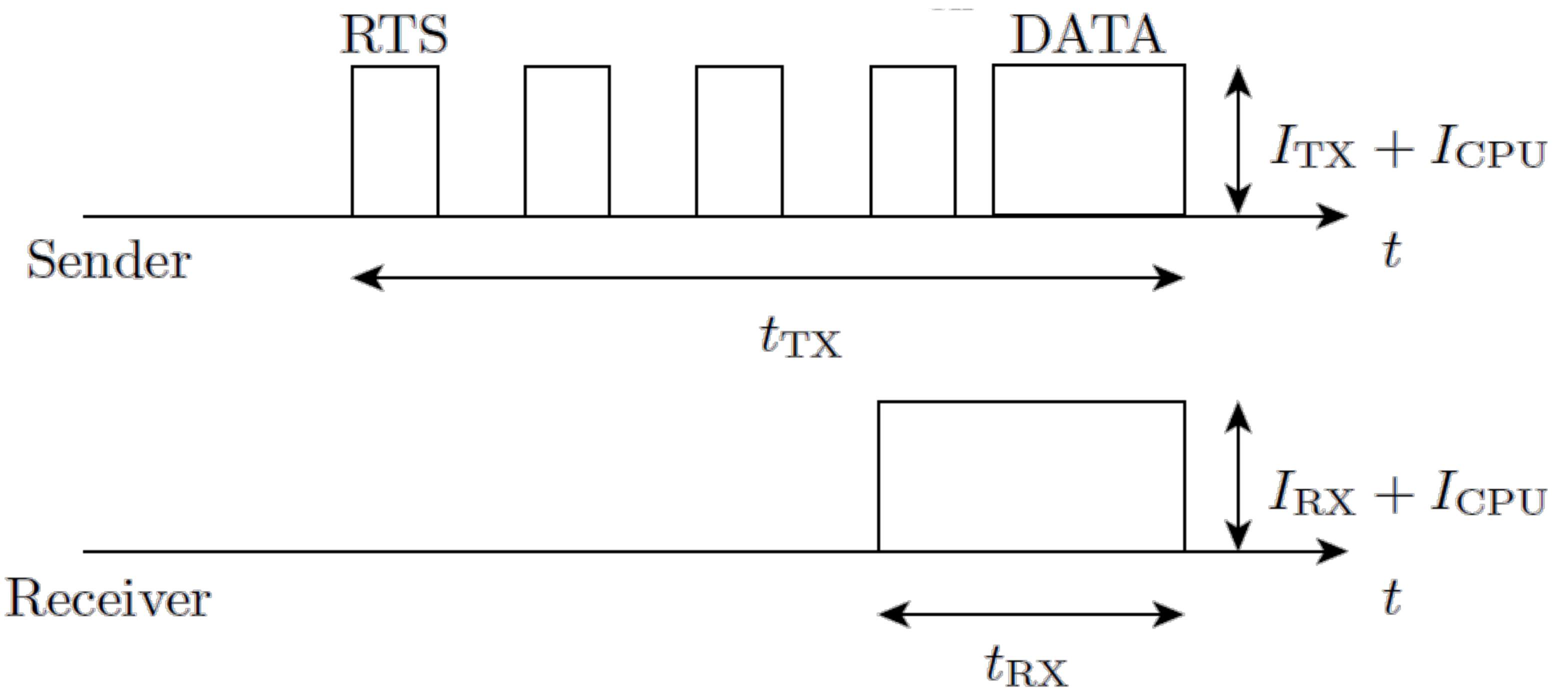
$$d = \frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}}$$

- d usually ranges between 0.01 → 0.1 (nodes are awake 1 to 10% of the time)

MAC: access protocol

X-MAC is considered as the channel access technique

- allows asynchronous communication
- preamble-based
- transmitter initiated



Optimization Problem P1

$$
\begin{aligned}
t_{\mathrm{U}} &\rightarrow \text{average inter-packet transmission time} \\
t_{\mathrm{dc}} &\rightarrow \text{duty cycle period } (t_{\mathrm{dc}} = t_{\mathrm{on}} + t_{\mathrm{off}}) \\
I_{\mathrm{OUT}} &\rightarrow \text{average current drained} \\
u &\rightarrow \text{maximum current drained} \\
(u &\rightarrow \text{control action set by P2})
\end{aligned}
$$

Optimization Problem P1

$$\begin{aligned} \underset{t_{\mathrm{U}},t_{\mathrm{dc}}}{\text{maximize}}\ & f_{\mathrm{U}} \\ \text{subject to: } & I_{\mathrm{OUT}} \le u, \\ & r_x \ge 0,\ \forall x \in \chi_N, \\ & t_{\mathrm{U}} \ge 0,\ t_{\mathrm{dc}} \ge t_{\mathrm{on}}. \end{aligned}$$

$$f_{\mathrm{U}} = 1/t_{\mathrm{U}} :\ \text{pkt-TX rate [pkt/s]}$$

- Constraints are *posynomials* → convex optimization is possible
- Closed-form solution is also possible

Optimization Problem P1

- We fix a network topology
- We fix a MAC protocol
- We fix a routing tree
- We specify all energy consumption figures (TX, RX, etc.)

result

$$(t^*_{\mathrm{U}}, t^*_{\mathrm{dc}})$$

- pair that maximizes the throughput [pkts/s]
- keeping the average energy consumption equal to u

System Parameters

Timings

$$t_{\text{on}} = 6 \text{ ms}$$

$$t_{\text{off}} = 14 \text{ ms}$$

$$t_{\text{int}} = 10 \text{ ms}$$

$$t_{\text{CPU}} = 40 \text{ ms}$$

$$t_{\text{RPL}} = 6 \text{ h}$$

Energy figures

$$i_{\text{TX}} = 10 \text{ mA}$$

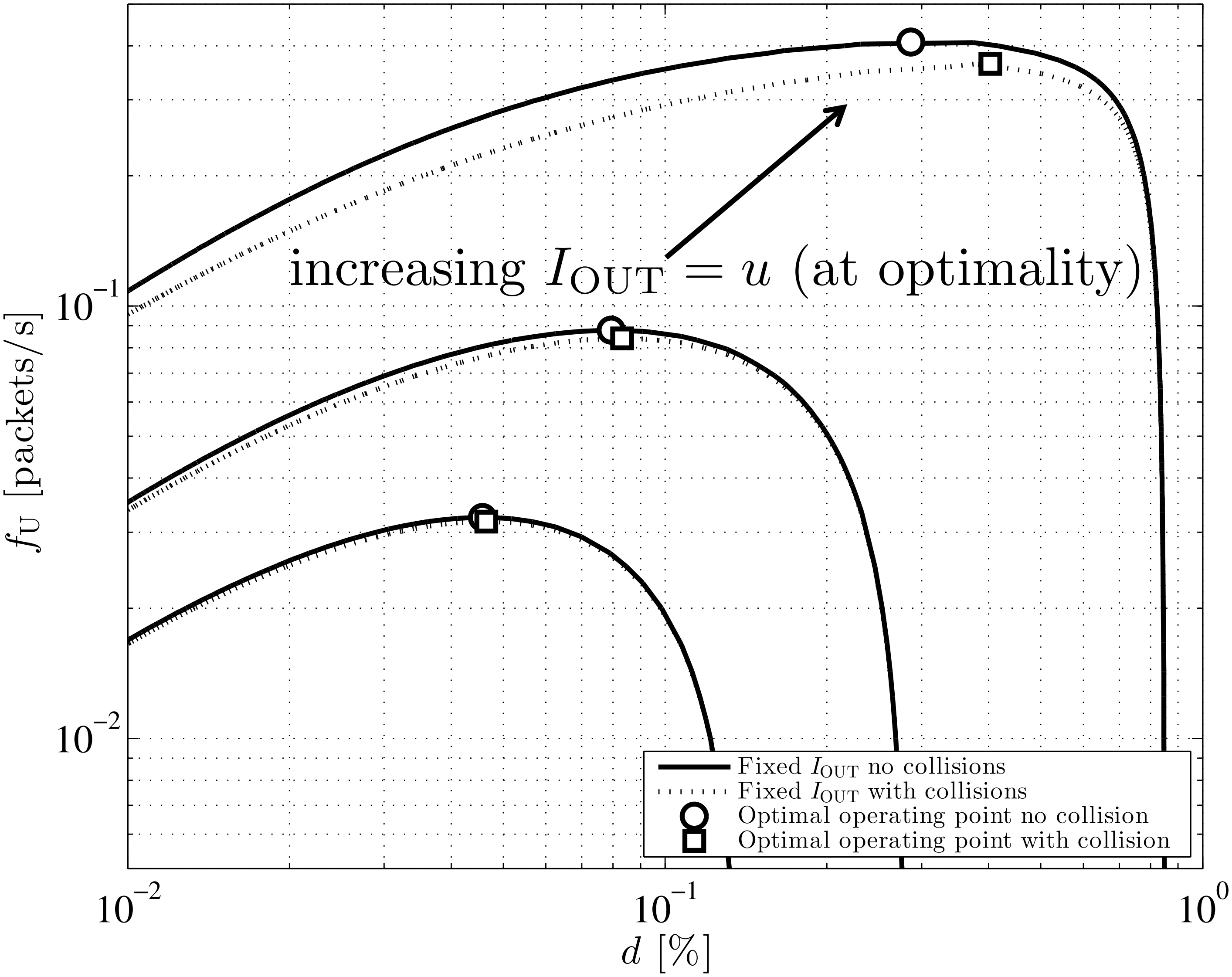
$$i_{\text{RX}} = 8.7 \text{ mA}$$

$$i_{\text{CPU}} = 26.6 \text{ mA}$$

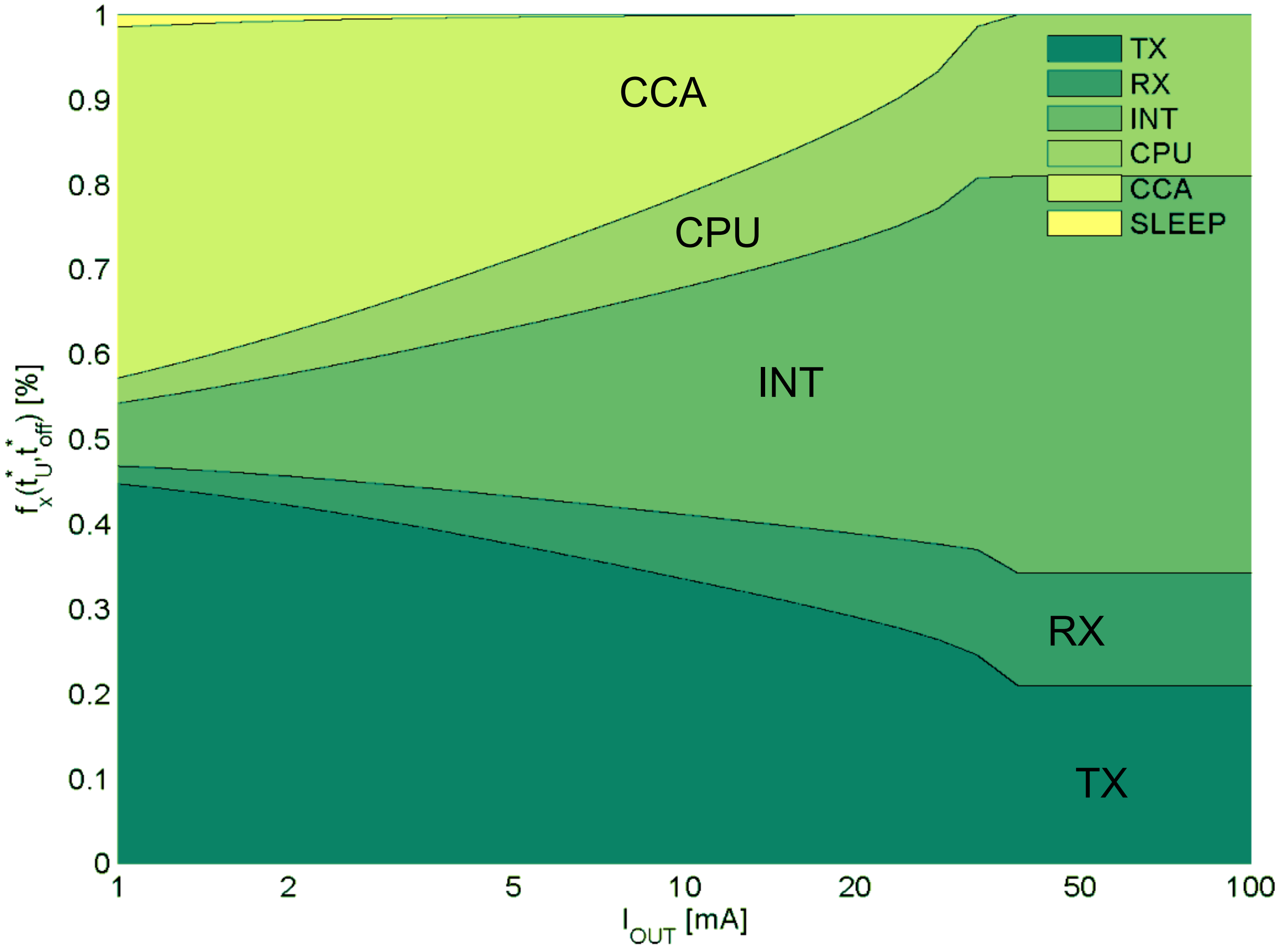
$$i_{\text{S}} = 0.015 \text{ mA}$$

$$K_{\text{U}} = 10$$

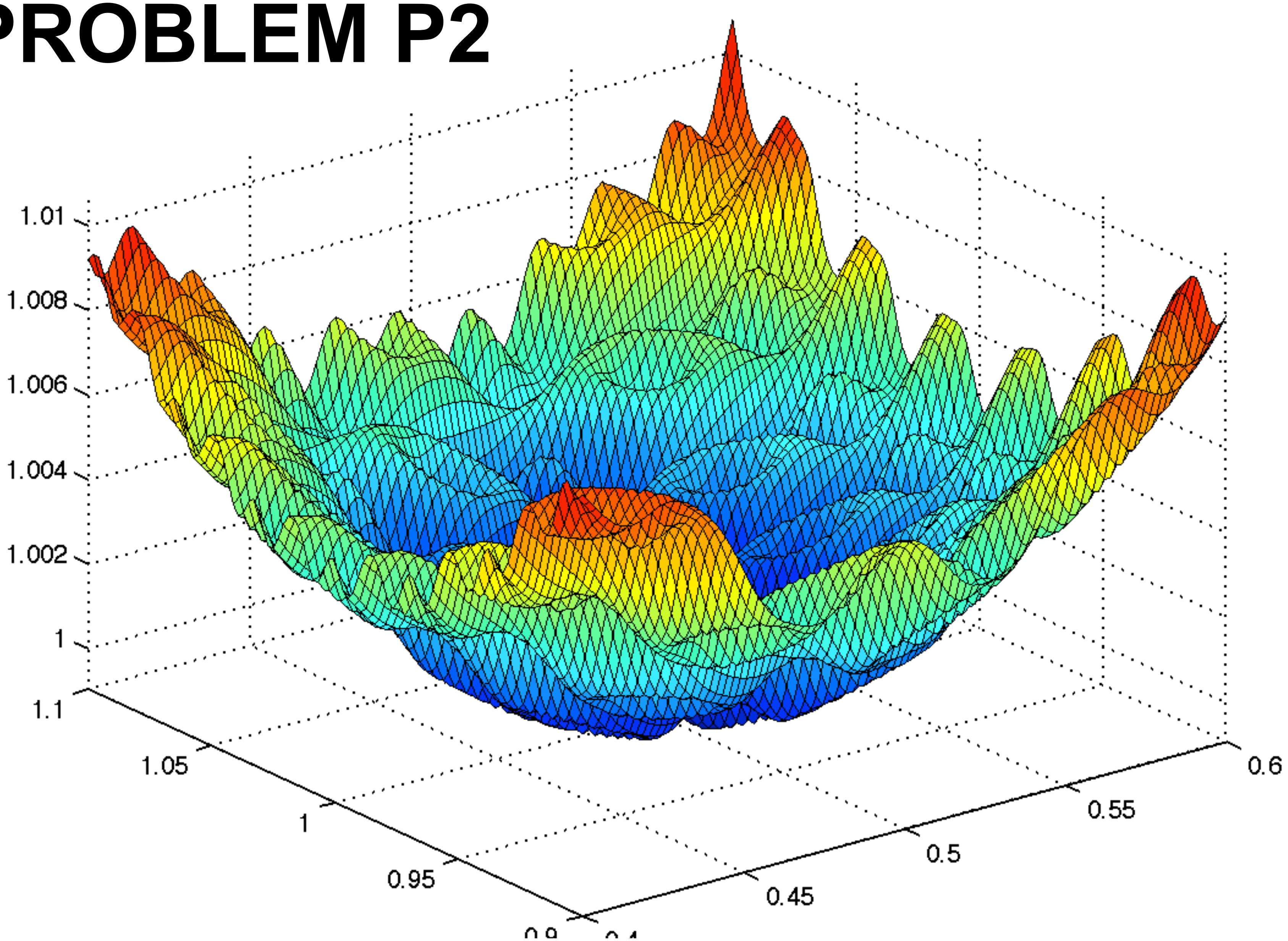
P1: Problem Solution



Energy Consumption Share



PROBLEM P2



Problem formulation

System state $S(k)=(x_b(k),x_s(k))$

- Energy buffer state $x_b(k)$ @ beginning of stage k
- Energy source state $x_s(k)$ during stage k

Control u_k

- Current drained by the node (I_{out})
- Immediate reward $R(u_k,S(k))$ (throughput [pkt/s])

Stage-Cost $C(u_k,S(k))$

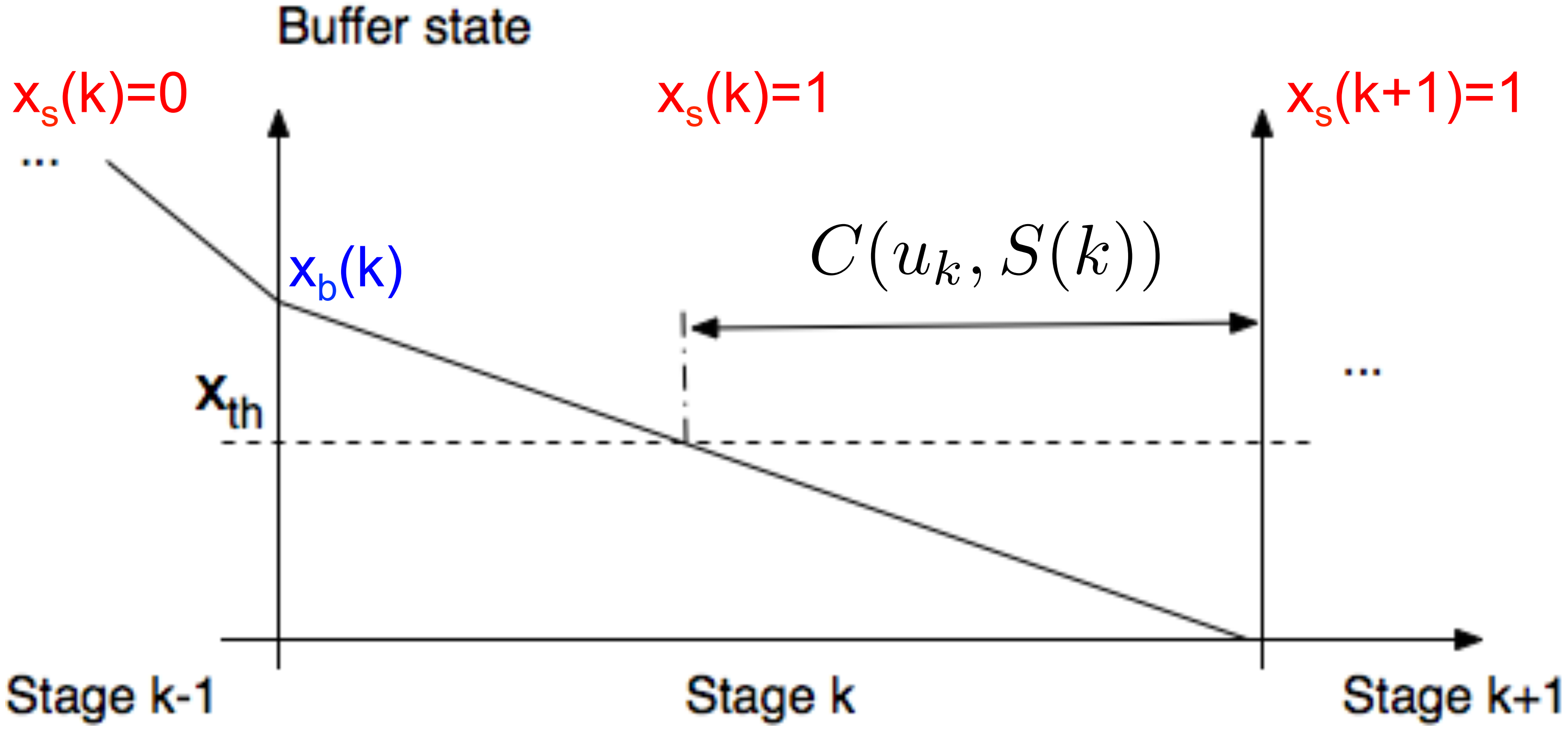
- Average time spent with $x_b(k)<x_{th}(k)$ (tunable threshold)

Stage-Reward $R(u_k,S(k))$

- Total reward: integral of $R(u_k,S(k))$ over the solution path

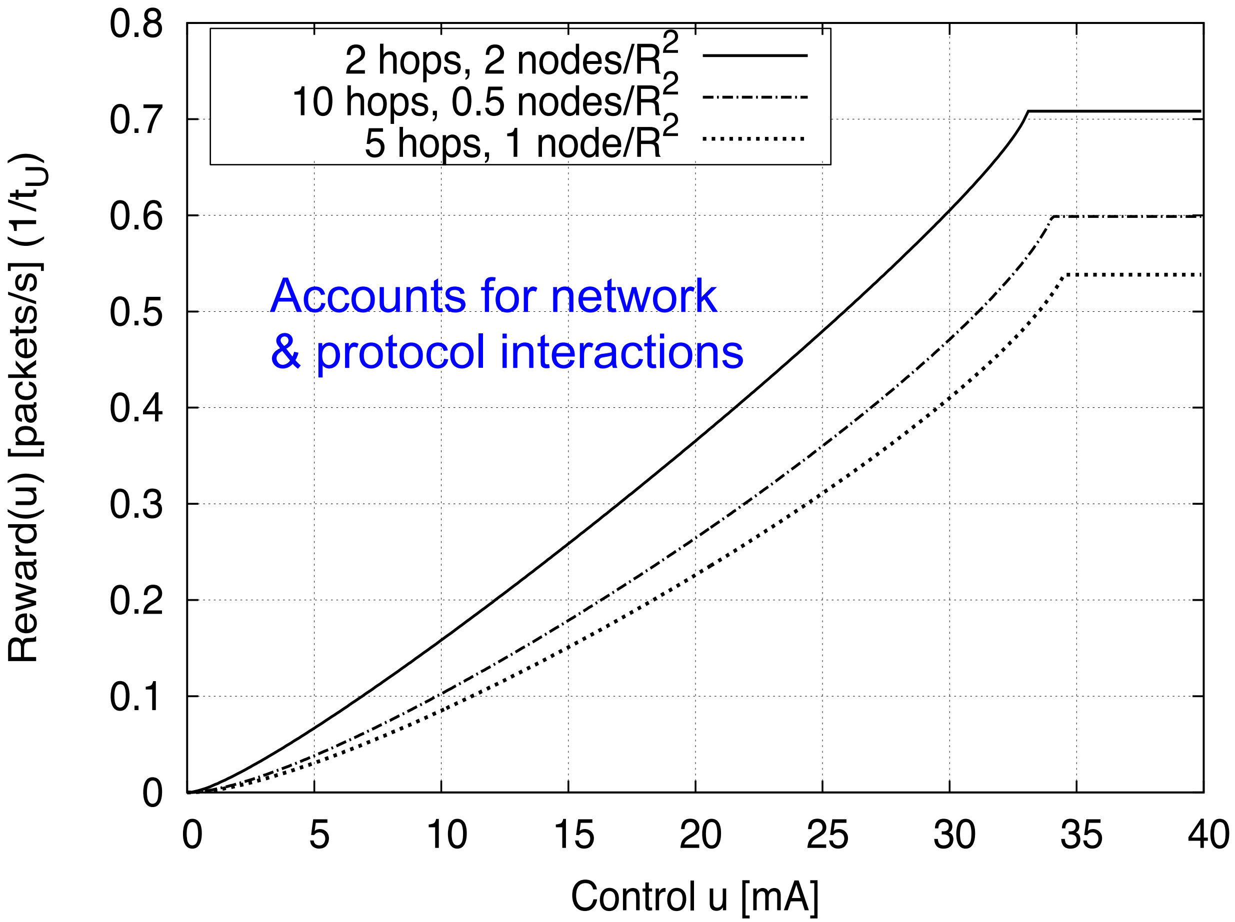
Single Stage Cost

Average single-stage cost: duration of time interval where $x_b(k) < x_{th}$



Single Stage Reward

$$R(u_k, S(k)) = 1/t^*_{\mathrm{U}}$$



Accounts for network & protocol interactions

Average reward over a single stage k:

- $R(u_{k,}S_k)$ multipled by the time during which x_b>0 (non-empty buffer)
- $R(u_{k,}S_k)$ is obtained from the static energy consumption analysis of part A

Optimal Policies

$$\underset{\pi}{\text{maximize}}\left\{\lim_{N\to+\infty} E\left[\sum_{k=0}^{N-1}\alpha^k R(u_k, S(k))\middle| S(0)\right]\right\}$$

$$\text{subject to: } \lim_{N\to+\infty} E\left[\sum_{k=0}^{N-1}\alpha^k C(u_k, S(k))\middle| S(0)\right] \leq C_{\text{th}}$$

Meaning

- Find the policy π: $u_k(S(k)$, for all $S(k)$ that maximizes the expected long-term throughput (reward)
- Subject to the fact that the long-term expected cost is smaller than a threshold

Remember: cost=fraction of time during which the energy buffer state is below x_{th}
Discount factor: control the look-ahead capability of the optimal policy

Lagrangian Reward

$$R_{\mathcal{L}}(u_k, S(k)) = R(u_k, S(k)) - \lambda C(u_k, S(k))$$

A lagrangian λ is introduced to balance

- Costs $C(u_k,S(k))$
- Rewards $R(u_k,S(k))$

The lagrangian is part of the solution

1. Choose λ
2. Solve optimal problem for this λ
3. Iterate over λ to find global optimum

Lagrangian Reward - rationale

$$R_{\mathcal{L}}(u_k, S(k)) = R(u_k, S(k)) - \lambda C(u_k, S(k))$$

- Large λ: cost prevails
  - Small reward
  - Small cost → cost constraint is satisfied whp
    → λ can be decreased
- Small λ: reward prevails
  - High reward (more aggressive policies)
  - Large cost → cost constraint is not satisfied
    → λ has to be increased

→ dichotomic search over λ

Lagrangian Bellman Equation

$$J(S(k)) = \max_{u_k \in U(S(k))} \left\{ \underbrace{E[R_{\mathcal{L}}(u_k, S(k))]}_{\text{Single-stage expected Lag. reward}} + \underbrace{\alpha \int_{-\infty}^{+\infty} J(S'(k+1)) h(q|x_s(k), u_k)}_{\text{Discounted future expected reward (from k+1 onwards)}} \right\}$$

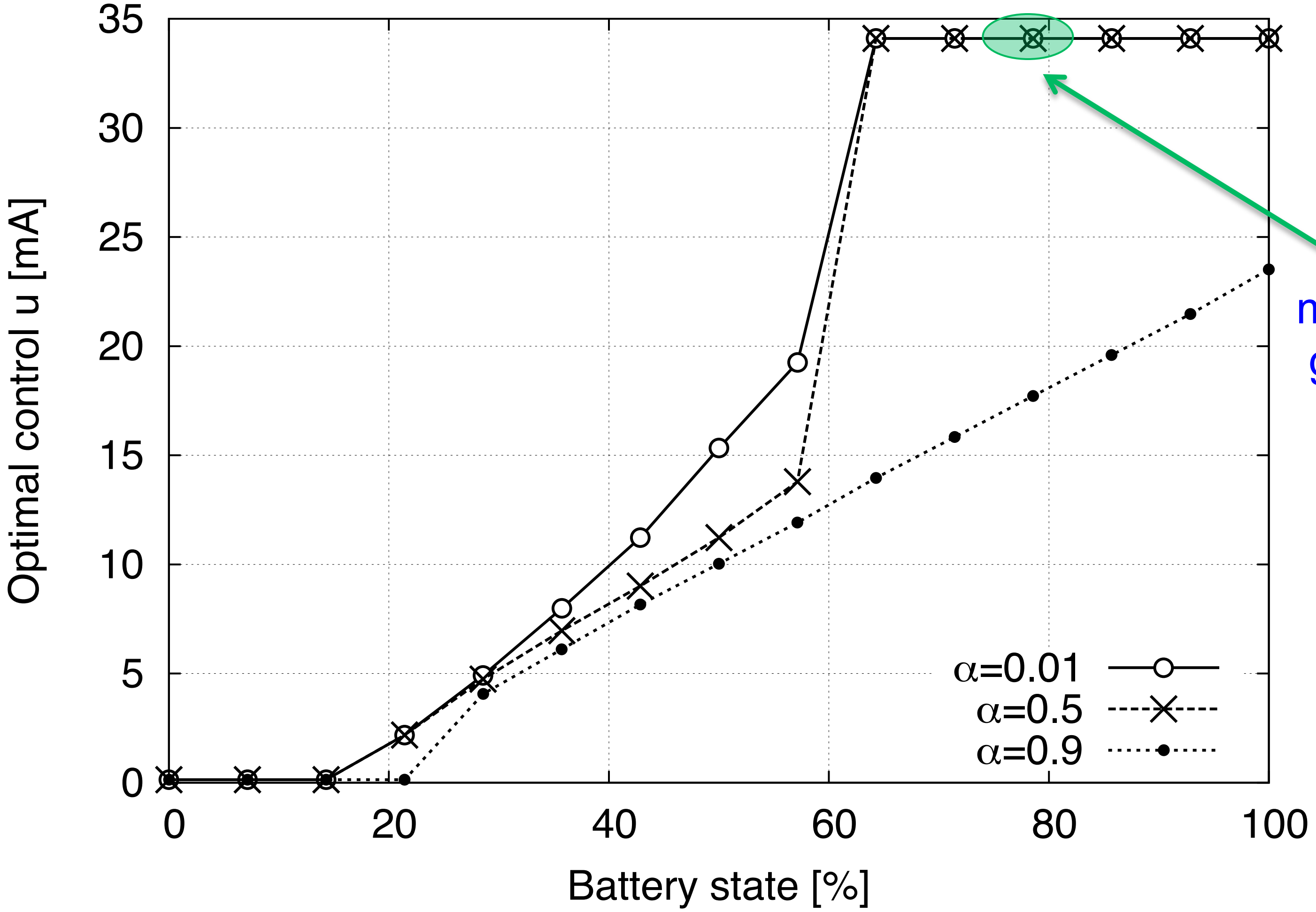
J(S(k)): expected reward from stage k onwards

$$\begin{aligned} S'(k+1) &= (x_s(k+1), x_b(k+1)) \\ &= (1 - x_s(k), \underbrace{\max\{\min\{q + x_b, Q\}, 0\}}_{\text{Accounts for min and max energy buffer size}}) \end{aligned}$$

Here!!!!!

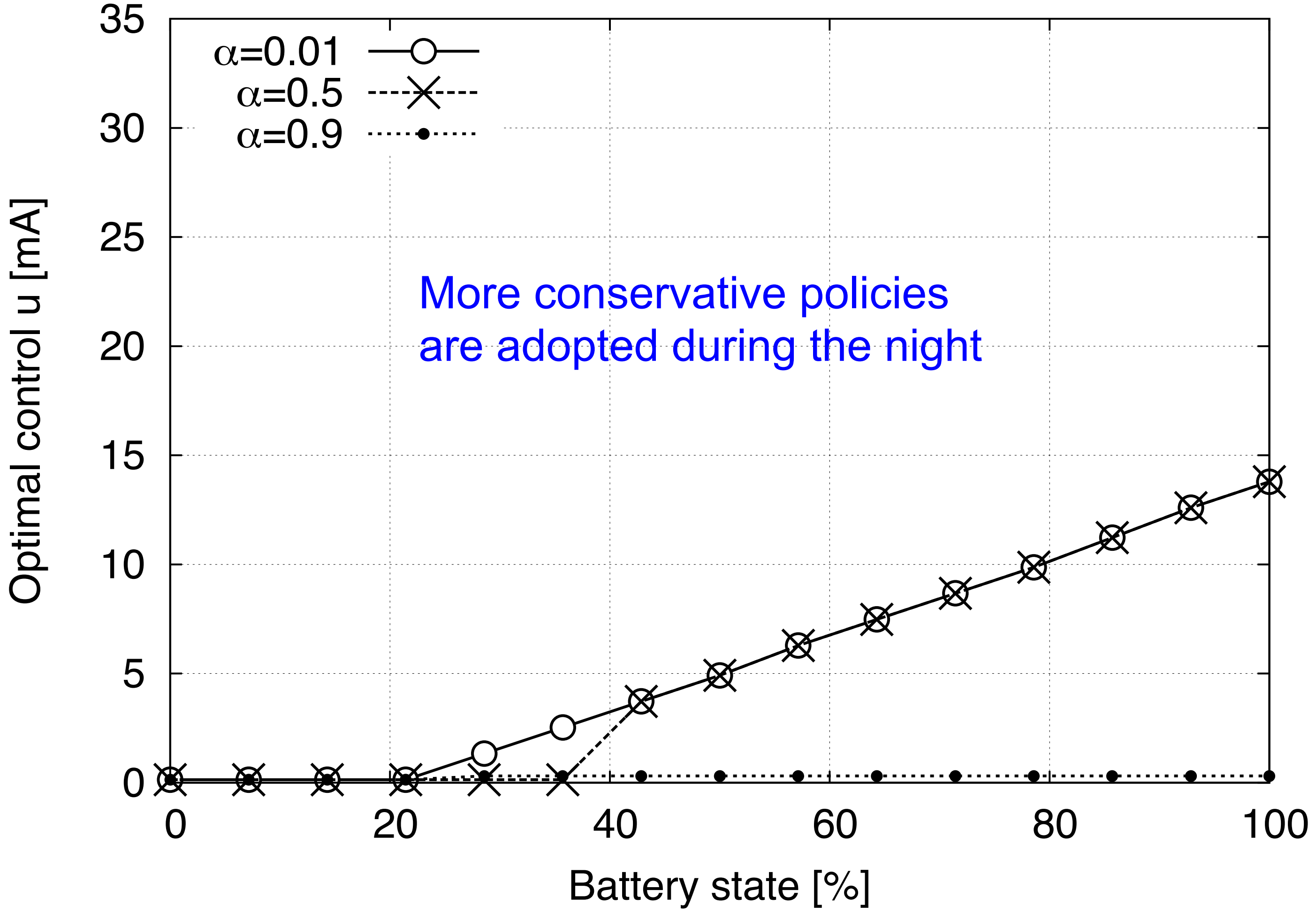
Results

Results – Policies vs α (discount) state $x_s=0$ (day)



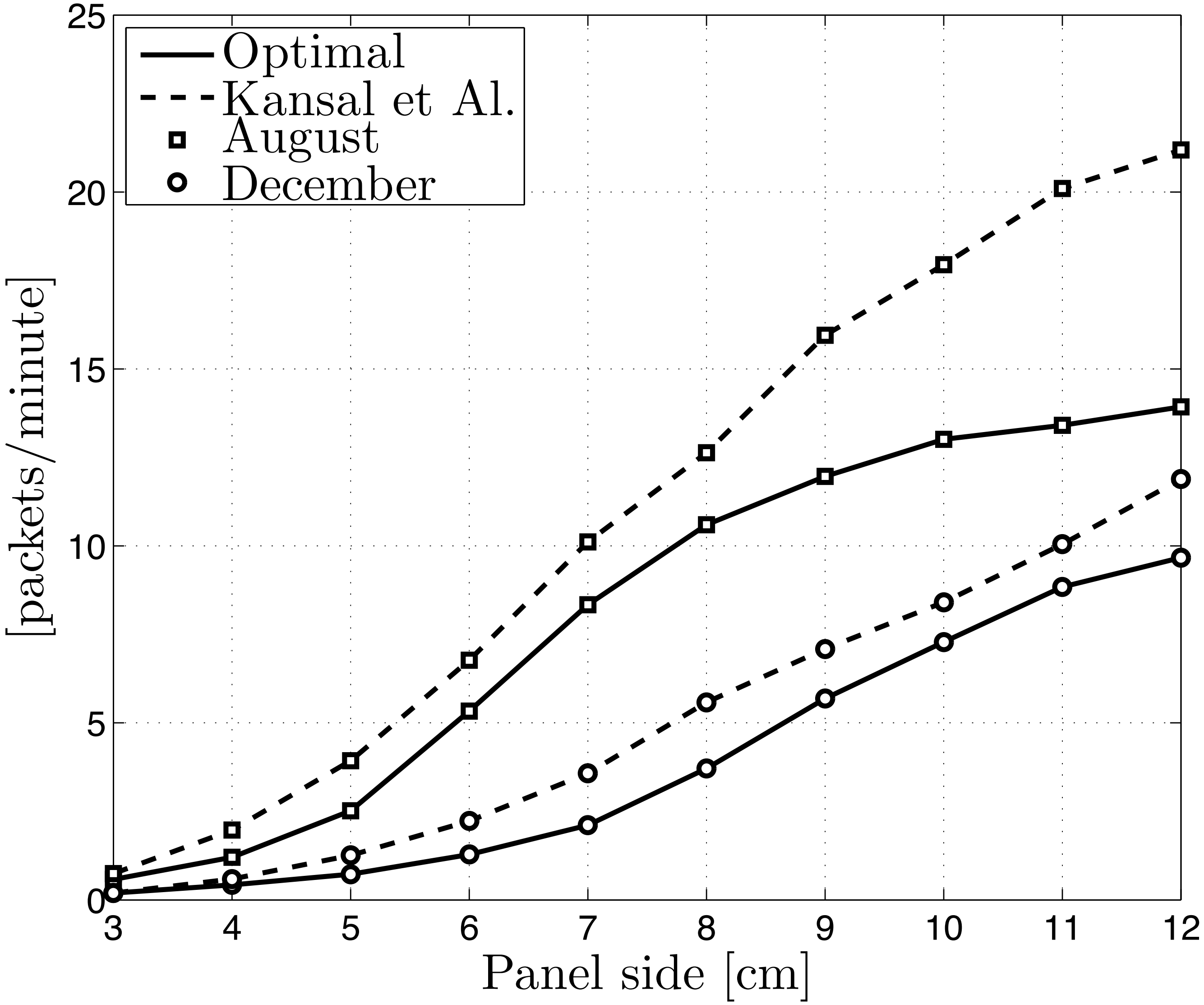
max control for the given parameters

Results – Policies vs α (discount) state x_s=1 (night)

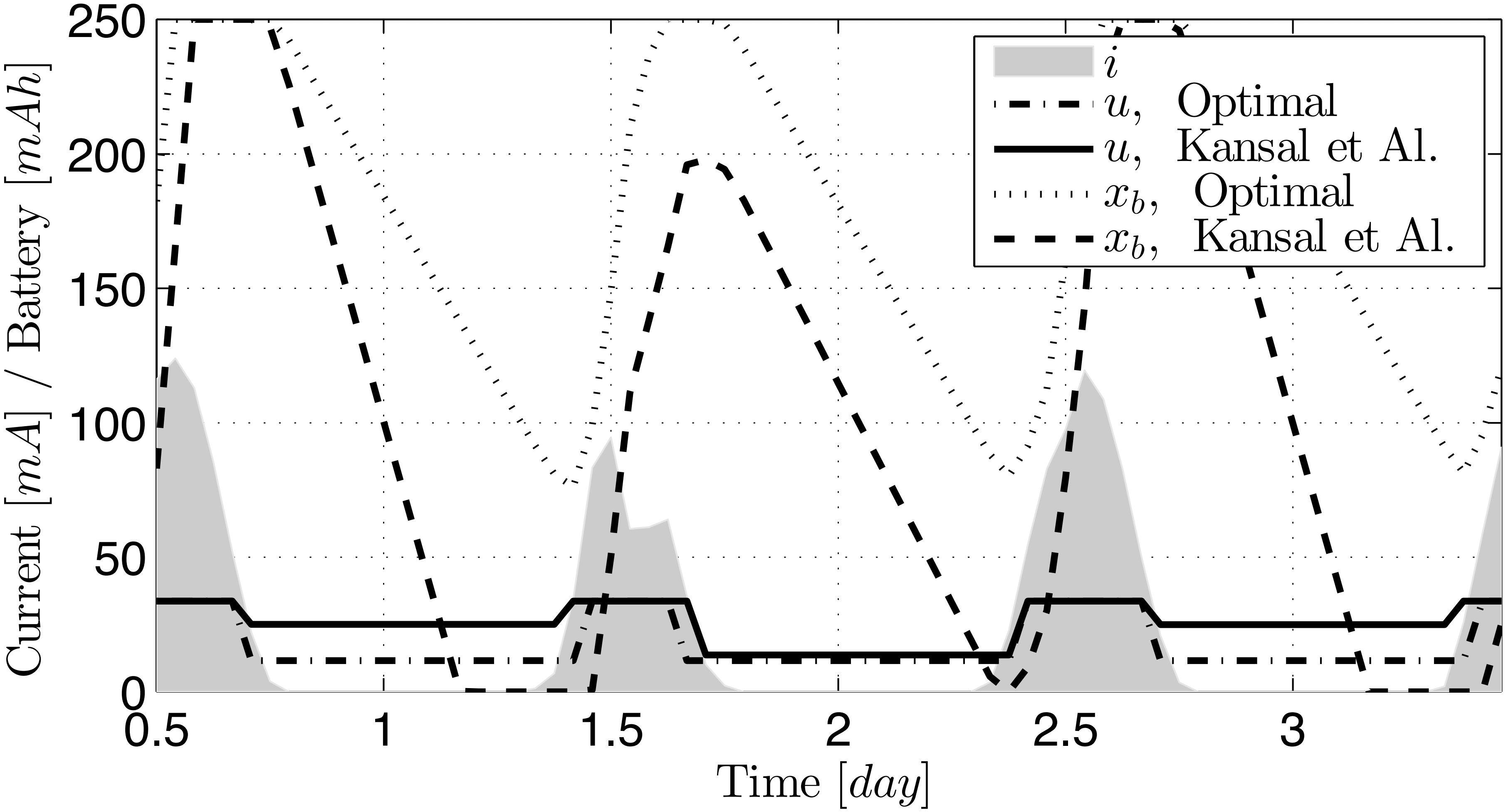


More conservative policies are adopted during the night

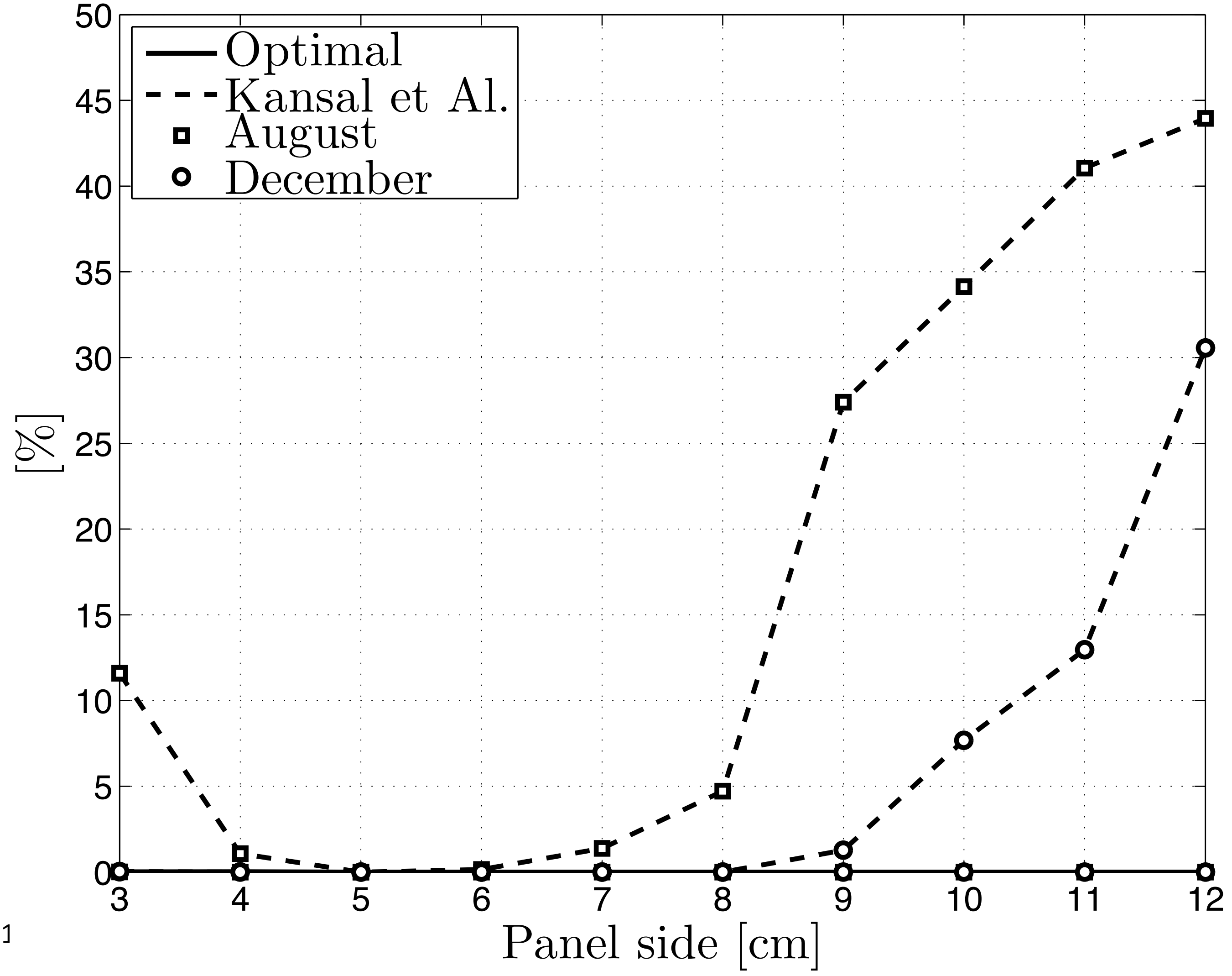
Throughput *vs* Panel Size



Outage *vs* Panel Size



Energy Outage *vs* Panel Size



Bibliography

[1] N. Bui and M. Rossi, “Staying Alive: System Design for Self-Sufficient Sensor Networks,“ *ACM Transactions on Sensor Networks*, accepted, 2015.

[2] M. Miozzo, D. Zordan, P. Dini and M. Rossi, “SolarStat: Modeling Photovoltaic Sources through Stochastic Markov Sources,” IEEE *EnergyCon*, Dubvronik, Croatia, May 2014.

[3] N. Bui and M. Rossi, “Dimensioning Self-Sufficient Networks of Energy Harvesting Embedded Devices,” *WifFex*, Kaliningrad, Russia, September 2013.

[4] A. Kansal, J. Hsu, S. Zahedi and M. B. Srivastava, “Power management in energy harvesting sensor networks,” *ACM Transactions on Embedded Computing Systems (TECS),* Vol. 6, No 4, 2007.

Thank You


THANK
YOU
GRACIAS
ARIGATO
SHUKURIA
DANKSCHEEN
BİYAN
SHUKRIA
TINGKI
TASHAKKUR ATU
YAQHANYELAY
SUKSAMA
EKHMET
GRAZIE
MEHRBANI
KOMAPSUMNIDA
MAAKE
PALDIES
BOLZÏN
MERCI
GOZAIMASHITA
EFCHARISTO
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MAKETAI
MINMONCHAR
MERASTAWHY
GAEJTHO
SANCO
LAH
TAVTAPUCH
MEDAWAGSE
AGUYJE
FAKAAUE
BAIKA

Backup Slides…

Problem 1:
Mathematical Details

Problem 1: topology

n_{c} number of children nodes, i.e., total number of nodes in the sub-tree rooted at the bottleneck

n_{i} number of interfering nodes (within the transmission range of the bottleneck)

n_{int} accumulated number of interfering packets from interfering nodes, accounting for endogenous (their own transmissions) and exogenous (transmissions of their children nodes) traffic

Problem 1: DATA TX, RX

$$f_{\mathrm{TX,DG}} = (1 + n_{\mathrm{c}})/t_{\mathrm{U}}$$

$$f_{\mathrm{RX,DG}} = n_{\mathrm{c}}/t_{\mathrm{U}}$$

Transmitted and received packets per second due to Data Gathering (DG)

Packet transmission time (including collisions)

$$t_{\mathrm{TX}} = t_{\mathrm{on}} + t_{\mathrm{off}}/2 + t_{\mathrm{data}} + (f'_{\mathrm{U}}/f_{\mathrm{U}} - 1)t_{\mathrm{dc}}$$

f'_{U} : TX frequency with collisions

f_{U} : TX frequency wo collisions

Problem 1: RPL & DODAG

- Destination Oriented Directed Acyclic Graph (DODAG)

- RPL defines new ICMPv6 messages:

- Dag Information Object (DIO): carries information that allows nodes to discover an DODAG instance, learn its config pars and select a parent node
- Destination Advertisement Object (DAO): used to propagate destination information upwards the DODAG
- Dag Information Solicitation (DIS): to solicitate the TX of a DODAG object from an RPL node (not used in the analysis)

Problem 1: DODAG upward routes

- Nodes periodically send link-local (broadcast) DIO messages
- Nodes listen for DIOs and use the information therein to construct a DODAG or maintain an existing one
- Based on the info on the DIOs a node chooses its parent so as to minimize the cost toward the DODAG root
- Analysis: DIOs are periodically sent by the nodes at a rate

$$1/t_{\mathrm{rpl}}$$

Problem 1: DODAG downward routes

- Nodes inform parents of their present and reachability to their descendants by sending a DAO message
- DAOs are aggregated at intermediate nodes while sent upstream
- DAOs propagate from the leaves to the DODAG root node

- Analysis: DAOs are sent by the leaf nodes at a rate $1/t_{\mathrm{rpl}}$

Problem 1: RPL TX, RX

1 DIO and 1 DAO msg from bottleneck, n_c DAOs from its children nodes:

$$f_{\mathrm{TX,RPL}} = (2 + n_{\mathrm{c}})/t_{\mathrm{rpl}}$$

1 DIO from parent, n_c DAOs from children nodes, n_i DIOs from inter. nodes:

$$f_{\mathrm{RX,RPL}} = (1 + n_{\mathrm{i}} + n_{\mathrm{c}})/t_{\mathrm{rpl}}$$

NOTE: DIOs are not treated as interference as they are broadcast (*ergo* they are received and treated as legitimate packets)

Problem 1: interference

Rate of interfering packets:

$$f_{\mathrm{INT}} = n_{\mathrm{int}}(1/t_{\mathrm{U}} + 1/t_{\mathrm{rpl}})$$

$$\begin{cases} 1/t_{\mathrm{U}} & \text{TX rate for data packets} \\ 1/t_{\mathrm{rpl}} & \text{TX rate for RPL DODAG control packets} \end{cases}$$

Problem 1: current consumption figures

TX time for a single pkt transmission

$$I_{\mathrm{TX}} = (i_{\mathrm{c}} + i_{\mathrm{t}})\boxed{[t_{\mathrm{dc}}/2 + t_{\mathrm{on}}/2 + t_{\mathrm{data}} + (f'_{\mathrm{U}}/f_{\mathrm{U}} - 1)t_{\mathrm{dc}}]}\times$$

$$\times\boxed{[(1 + n_{\mathrm{c}})/t_{\mathrm{U}} + (2 + n_{\mathrm{c}})/t_{\mathrm{rpl}}]}$$

transmissions rate [pkt/sec]

$$I_{\mathrm{RX}} = (i_{\mathrm{c}} + i_{\mathrm{r}})t_{\mathrm{data}}[n_{\mathrm{c}}/t_{\mathrm{U}} + (1 + n_{\mathrm{c}} + n_{\mathrm{i}})/t_{\mathrm{rpl}}]$$

$$I_{\mathrm{INT}} = (i_{\mathrm{c}} + i_{\mathrm{r}})t_{\mathrm{int}}n_{\mathrm{int}}(1/t_{\mathrm{U}} + 1/t_{\mathrm{rpl}})$$

$$I_{\mathrm{CPU}} = i_{\mathrm{c}}t_{\mathrm{cpu}}K_{\mathrm{U}}/t_{\mathrm{U}}$$

$$I_{\mathrm{CCA}} = (i_{\mathrm{c}} + i_{\mathrm{r}})d_{\mathrm{c}}r_{\mathrm{IDLE}}$$

$$I_{\mathrm{OFF}} = i_{\mathrm{s}}(1 - d_{\mathrm{c}})r_{\mathrm{IDLE}}$$

Problem 1: current consumption figures

$$I_{\mathrm{TX}} = (i_{\mathrm{c}} + i_{\mathrm{t}})[t_{\mathrm{dc}}/2 + t_{\mathrm{on}}/2 + t_{\mathrm{data}} + (f'_{\mathrm{U}}/f_{\mathrm{U}} - 1)t_{\mathrm{dc}}]\times$$

$$\times\ [(1 + n_{\mathrm{c}})/t_{\mathrm{U}} + (2 + n_{\mathrm{c}})/t_{\mathrm{rpl}}]$$

$$I_{\mathrm{RX}} = (i_{\mathrm{c}} + i_{\mathrm{r}})t_{\mathrm{data}}[n_{\mathrm{c}}/t_{\mathrm{U}} + (1 + n_{\mathrm{c}} + n_{\mathrm{i}})/t_{\mathrm{rpl}}]$$

$$I_{\mathrm{INT}} = (i_{\mathrm{c}} + i_{\mathrm{r}})t_{\mathrm{int}}n_{\mathrm{int}}(1/t_{\mathrm{U}} + 1/t_{\mathrm{rpl}})$$

$I_{\mathrm{CPU}} = i_{\mathrm{c}}t_{\mathrm{cpu}}K_{\mathrm{U}}/t_{\mathrm{U}}$ ⇨ CPU time due to pkt generation (own traffic)

$I_{\mathrm{CCA}} = (i_{\mathrm{c}} + i_{\mathrm{r}})d_{\mathrm{c}}r_{\mathrm{IDLE}}$ ⇨ CPU time due to IDLING – RADIO ON

$I_{\mathrm{OFF}} = i_{\mathrm{s}}(1 - d_{\mathrm{c}})r_{\mathrm{IDLE}}$ ⇨ CPU time due to IDLING – RADIO OFF

with $r_{\mathrm{IDLE}} = 1 - r_{\mathrm{TX}} - r_{\mathrm{RX}} - r_{\mathrm{INT}} - r_{\mathrm{CPU}}$

Problem 1: closed-form solution

1) $$I_{\mathrm{OUT}}(t_{\mathrm{U}}, t_{\mathrm{dc}}) = \sum_{i \in \mathcal{X}} I_i$$

Total power consumption

2) $$\frac{\partial I_{\mathrm{OUT}}(t_{\mathrm{U}}, t_{\mathrm{dc}})}{\partial t_{\mathrm{dc}}} = 0 \rightarrow t^*_{\mathrm{dc}}(t_{\mathrm{U}})$$

Optimal duty-cycle → min. energy consumption for a given t_{U}

3) $$I_{\mathrm{OUT}}(t_{\mathrm{U}}, t^*_{\mathrm{dc}}(t_{\mathrm{U}})) - \boxed{u} = 0 \rightarrow t^*_{\mathrm{U}}(u)$$

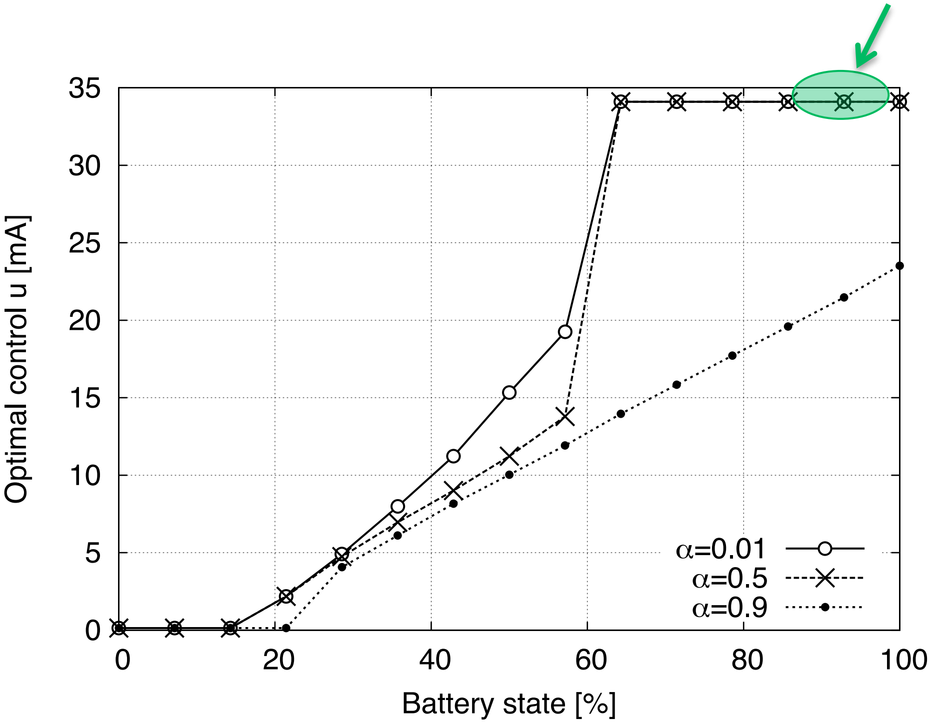
Max. current budget $u \in [u_{\min}, u_{\max}]$

$t^*_{\mathrm{U}}(u)$ ➡ Min. inter-packet TX time for given current budget u

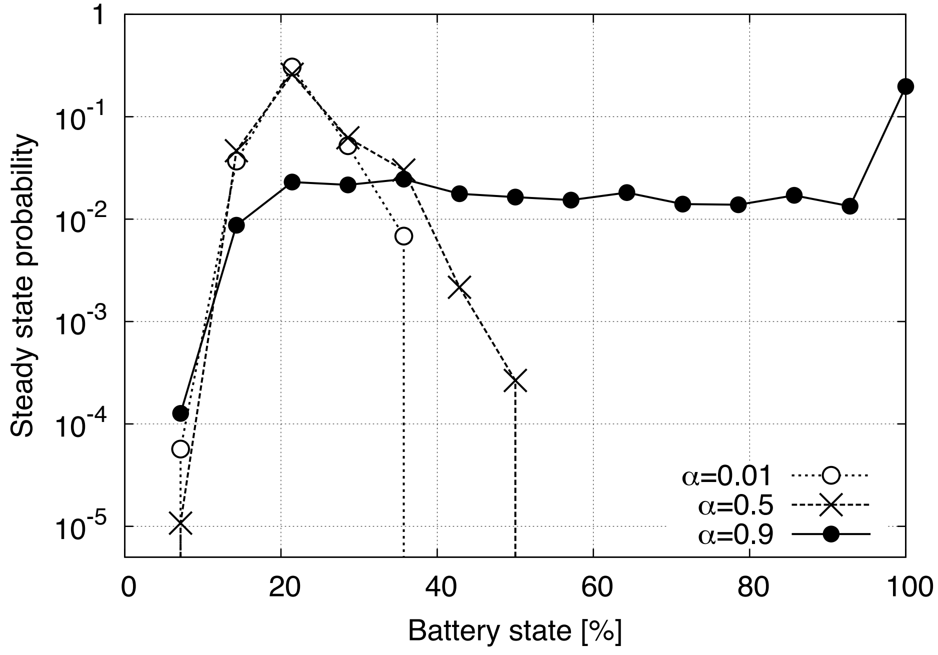
Optimal Policies: Additional Results

Results – Policies vs α (discount) state x_s=0 (day)

max. allowed control for the given network

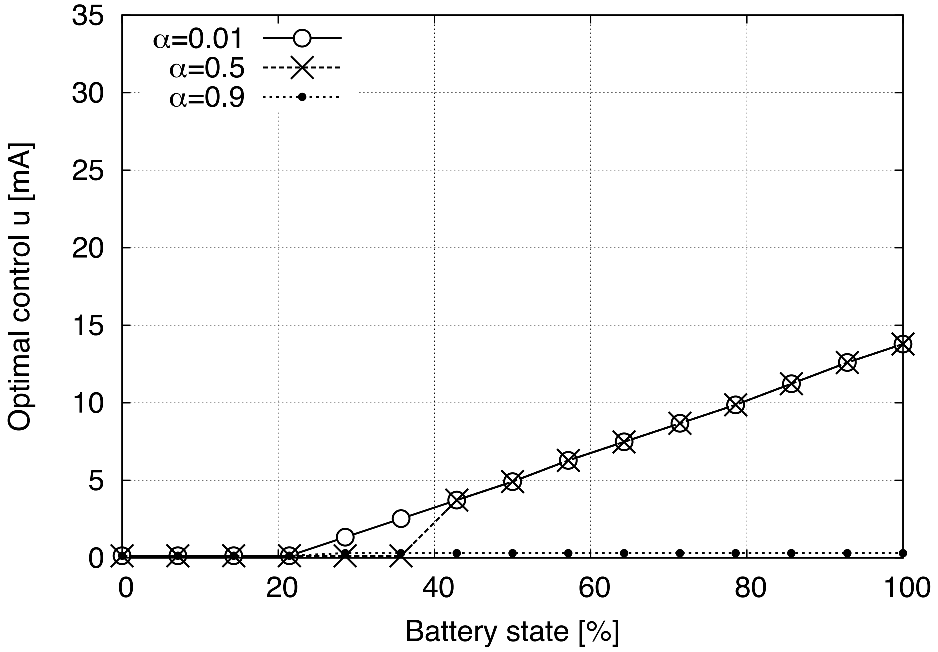


Optimal policy vs Buffer size

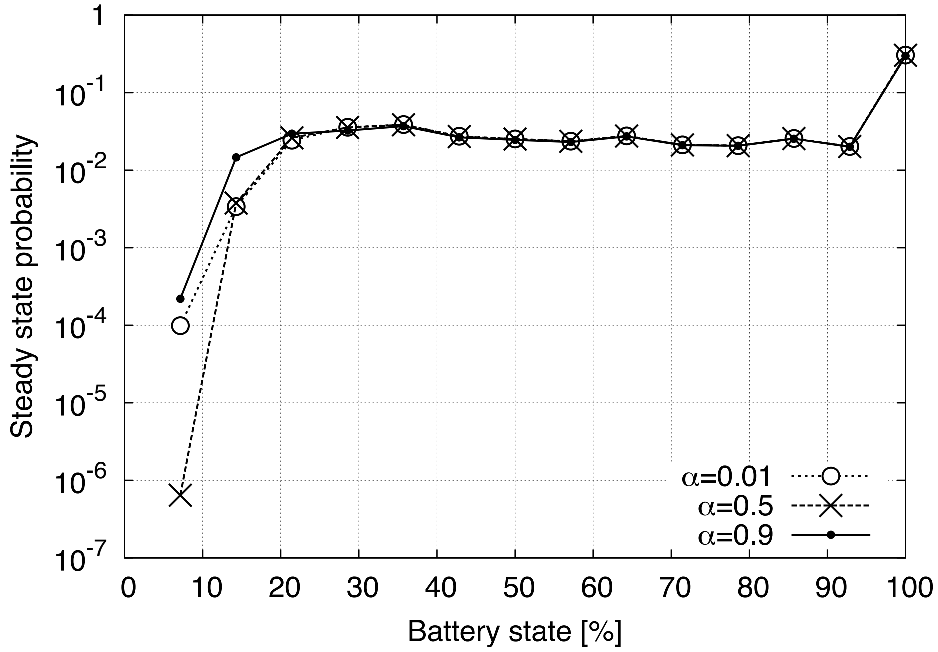


Corresponding stationary distribution

Results – Policies vs α state x_s=1 (night)



Optimal policy vs Buffer size

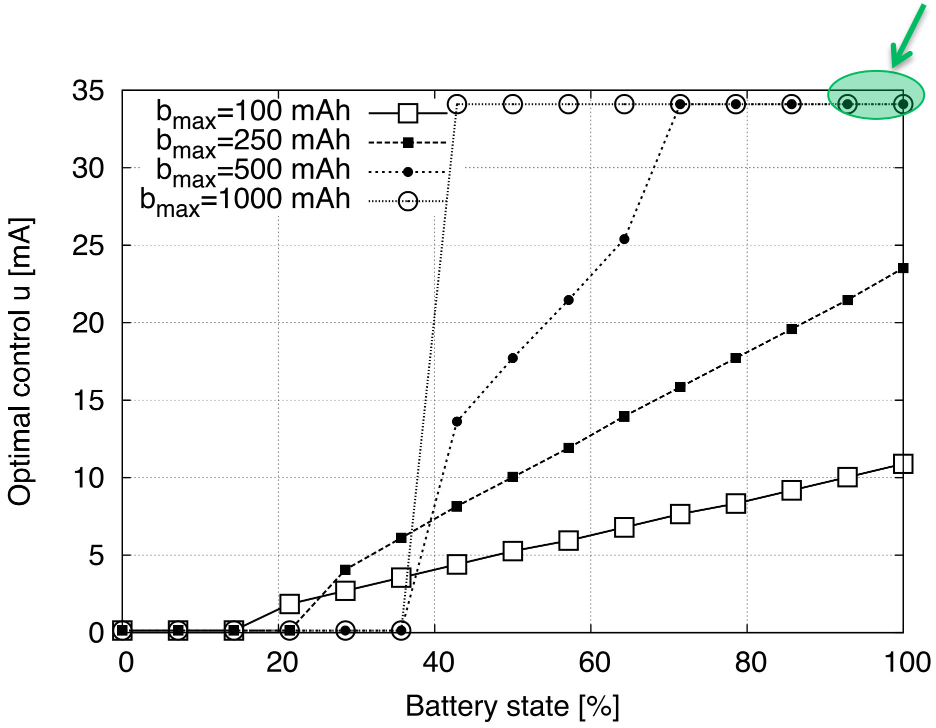


Corresponding stationary distribution

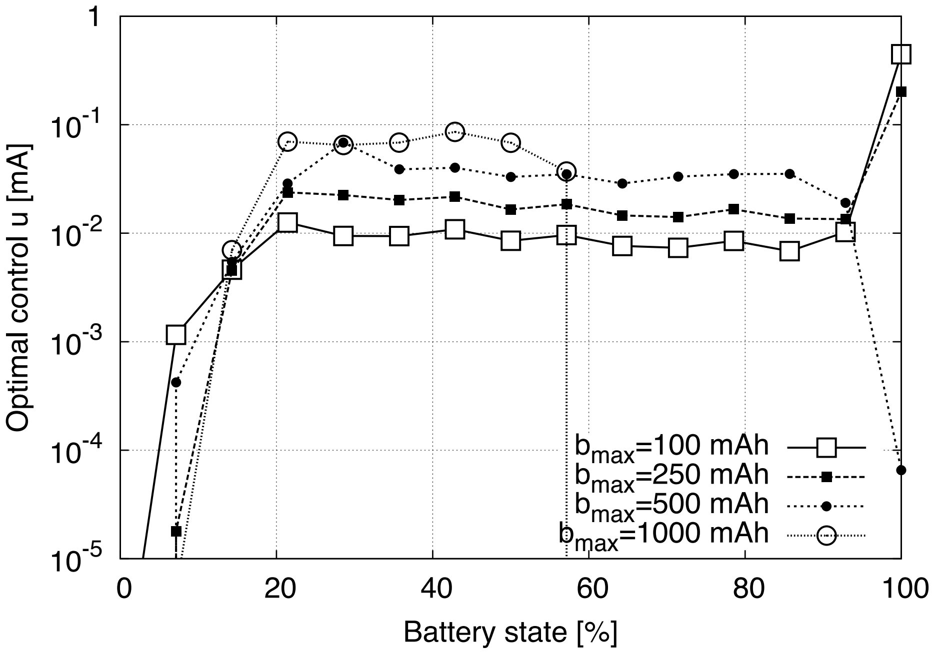
Results – Policies vs Buffer size

2-state EM - state x_s=0 (day)

max. allowed control for the given network

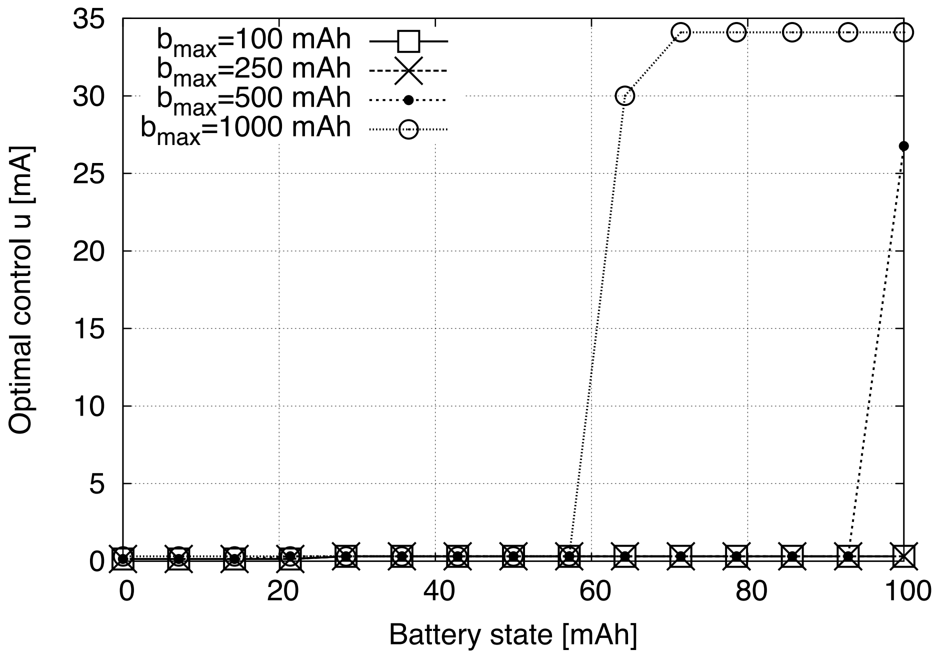


Optimal policy vs Buffer size

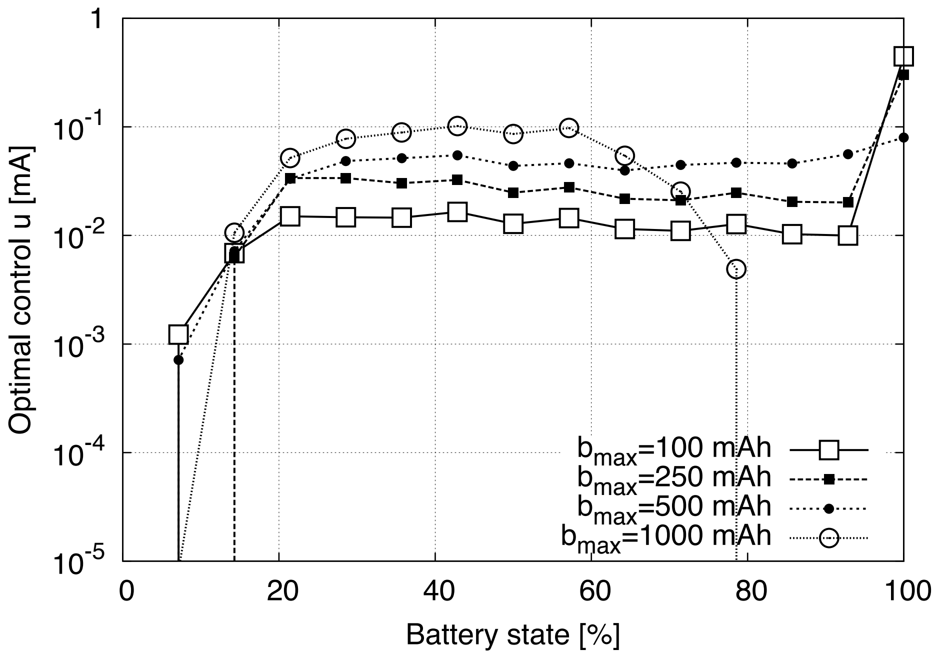


Corresponding stationary distribution

Results – Policies vs Buffer size
2-state EM - state x_s=1 (night)



Optimal policy vs Buffer size



Corresponding stationary distribution

Heuristic for Heterogeneous Energy Sources

Heuristic (1/2)

- DAOs are used to periodically report data (status of the nodes, etc.) to the DODAG root (i.e., the sink)
- We use these messages to periodically collect the energy buffer status of all nodes
- The sink decides which policy to adopt based on the minimum among all buffer states, $\min_i (B_i)$

Heuristic (2/2)

- The optimal policy is computed for the bottleneck node (worst case network parameters)
- This policy is used to decide the maximum energy consumption level for all nodes…
- …based on the minimum among all buffer states, $\min_i (B_i)$

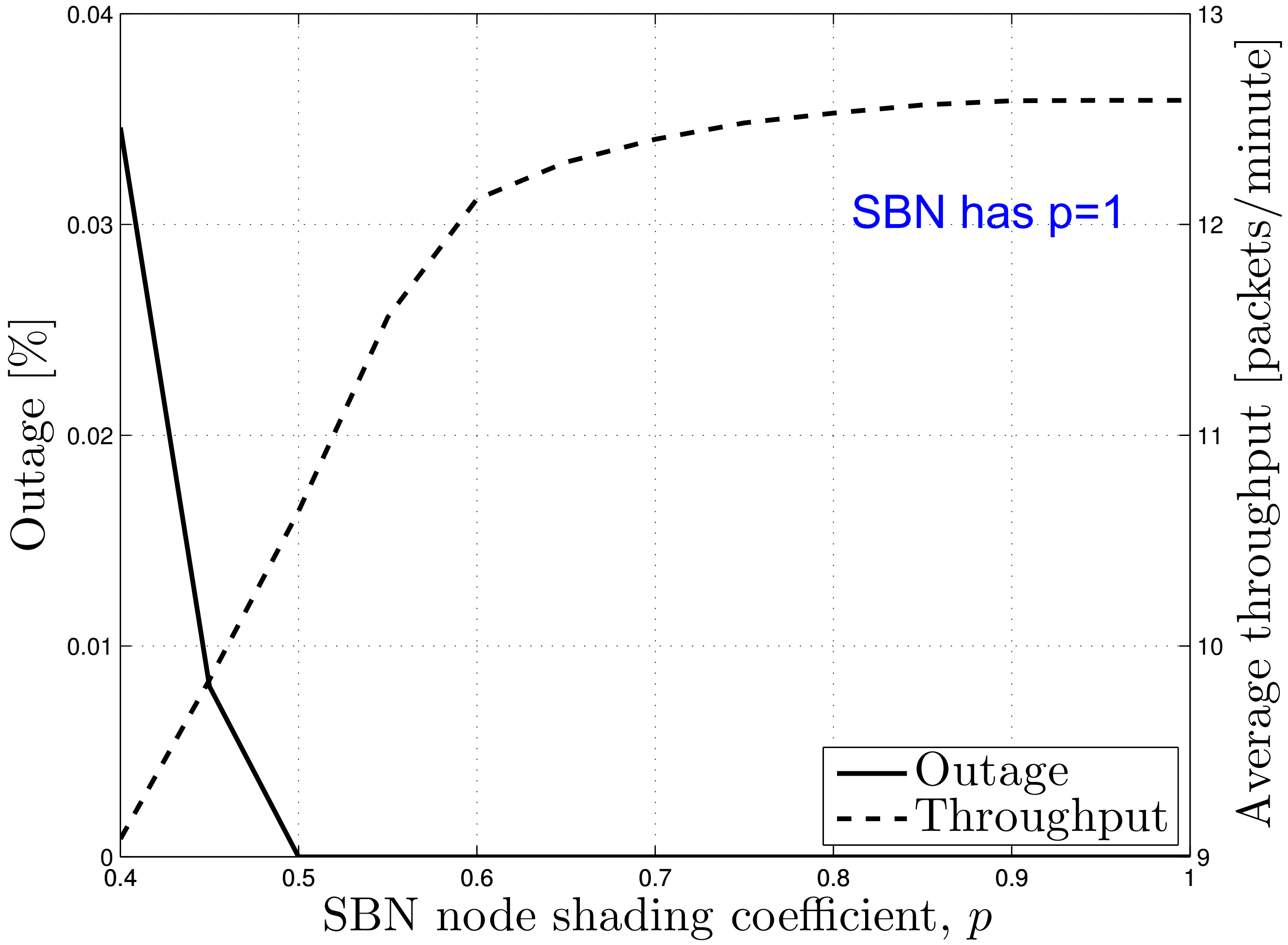
Outcome

- Policy will be suboptimal
- But will assure energy sustainability at all nodes

Heuristic – Results (1/2)

- BN: bottleneck node
- SBN: second-bottleneck node
  - Located in the sub-tree originating from the BN
  - With the second-highest energy consumption
- Worst case assumption
  - The BN has the same parameters n_i, n_{int} as the BN
  - As just one node less as its number of children, i.e., n_c-1

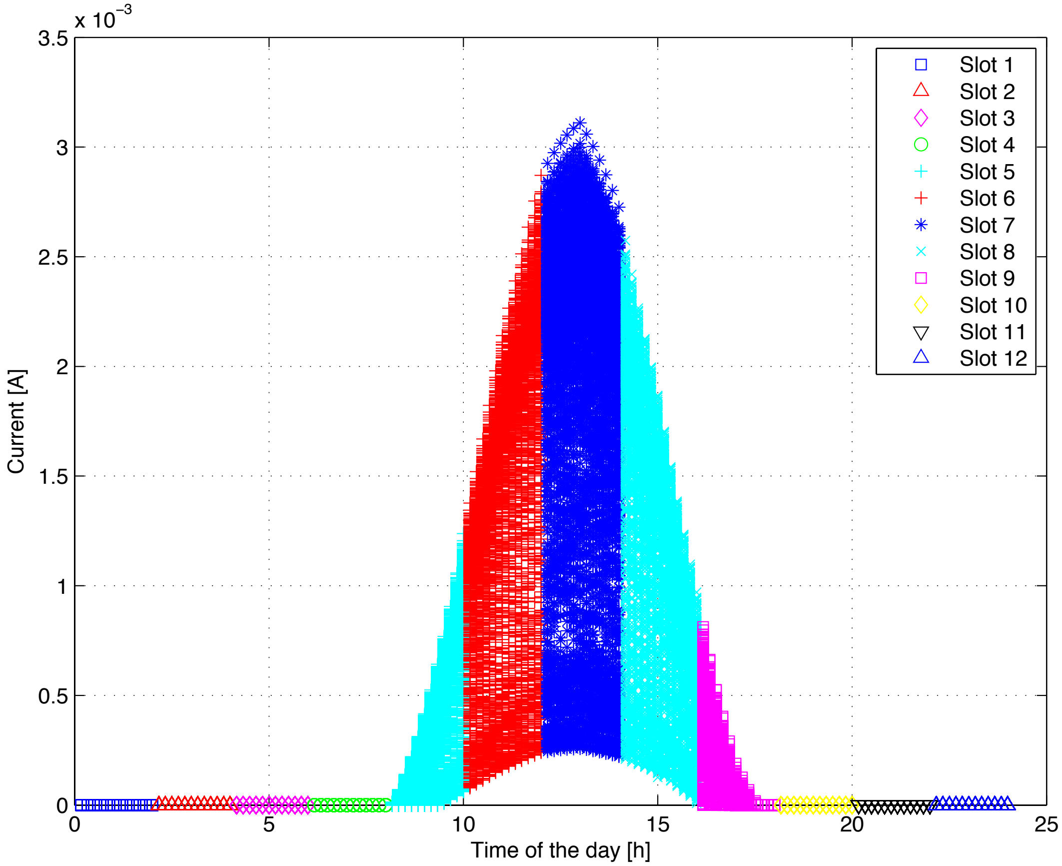
Heuristic – Results (2/2)



SBN has p=1

Energy Source Model: Additional Results

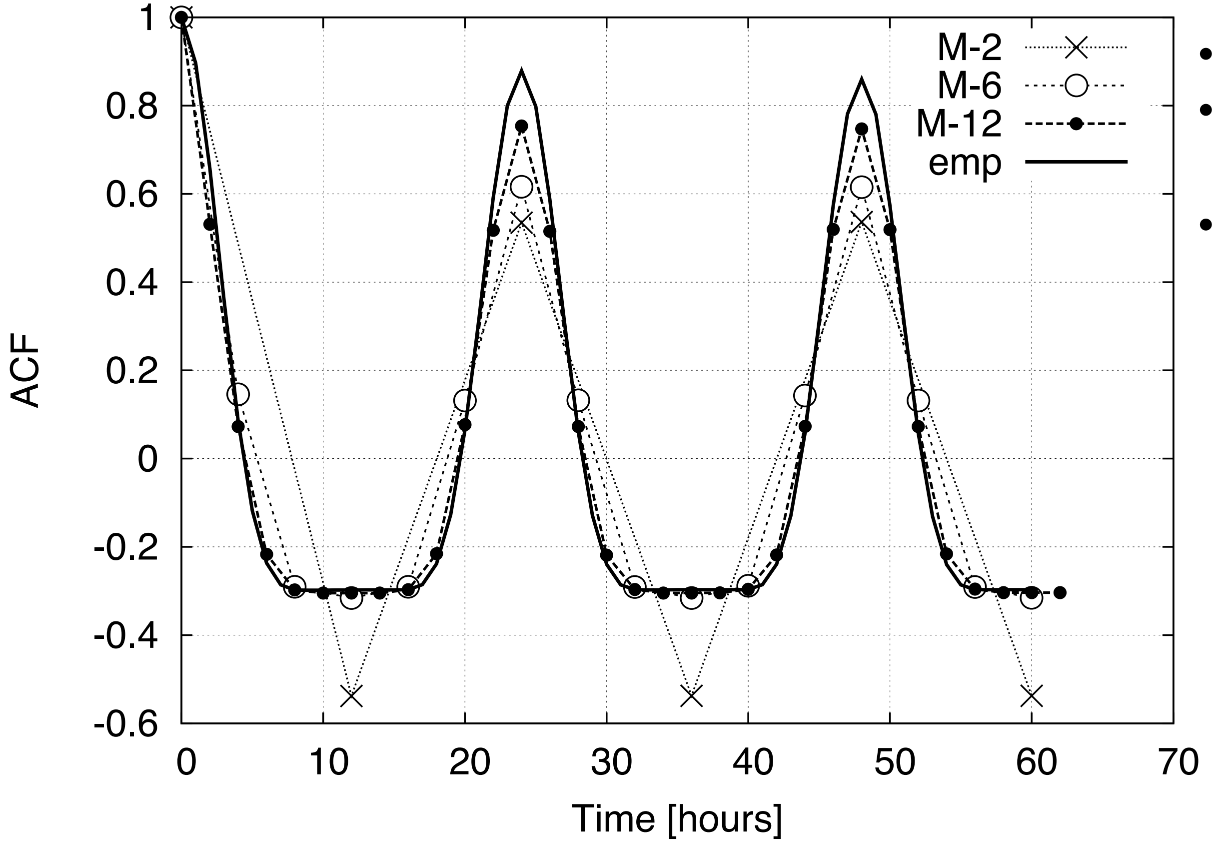
Slot-based clustering



- LA – January 1999-2010
- Slot-based data clustering

- Duration of "energy states"
    - constant
- Current harvested in each
    - Variable

Auto Correlation Function



- LA – January 1999-2010
- Slot-based data clustering

- Semi-MC with 2,4,6,12 states