Design of Communication Systems with Energy Harvesting Transmitters and Receivers

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Outline

- Introduction
- Retransmission-based multi-hop links
  1. PDP analysis
  2. Energy management policies
- Uncoordinated EH links
  1. Upper bounds
  2. Energy management policies
- Conclusions

Introduction

- 5G vision: connectivity to massive number of sensors
- Limited lifetime due to pre-charged batteries
- Potential solution: energy harvesting nodes (EHN)

- Harvesting sources
  - Solar, thermal, RF etc.

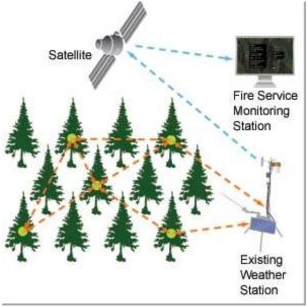

Figure: Forest fire monitoring

(http://news.mit.edu/2008/trees-0923)

Challenges

- Energy neutrality constraint (ENC)

$$\sum_{n=1}^{N} e_n \leq \sum_{n=1}^{N} \mathcal{E}_n, \text{ for all } N$$

e_n : energy consumed at n^{th} slot

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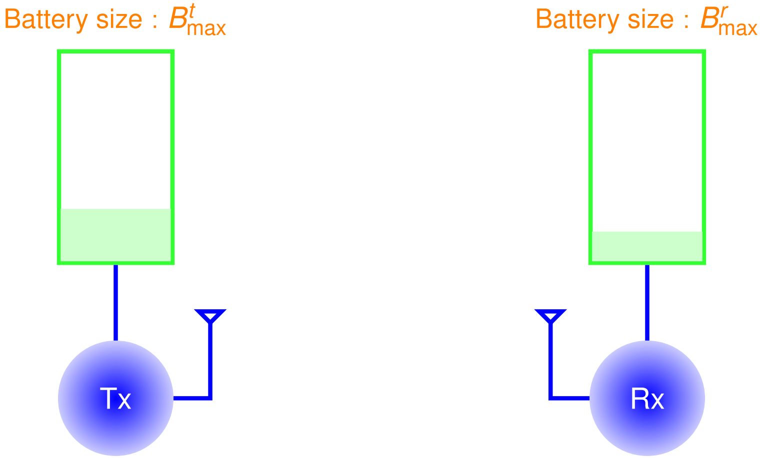
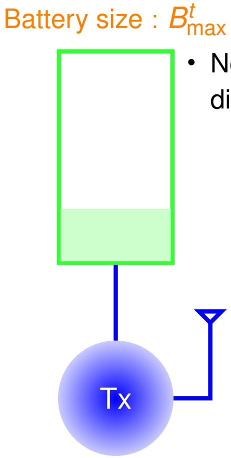
  - Goal shifts from energy conservation to judicious energy consumption
- Random and sporadic nature of the harvested energy
  - Necessitates the design of energy management policies
- Measurement of accurate state-of-charge (SoC) is difficult
  - SoC-independent policies

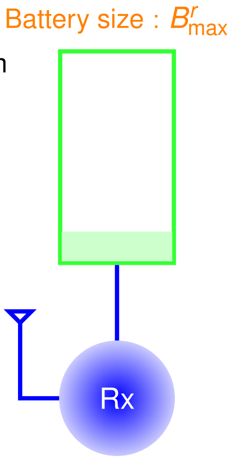
Challenges: EH Receivers



Challenges: Dual EH Links

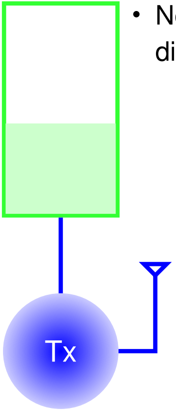


- Nodes harvest energy from distinct sources



Challenges: Dual EH Links

Battery size : B^t_{max}



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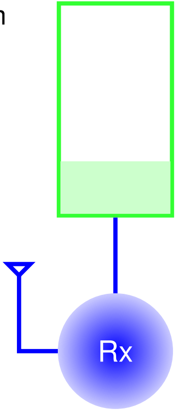

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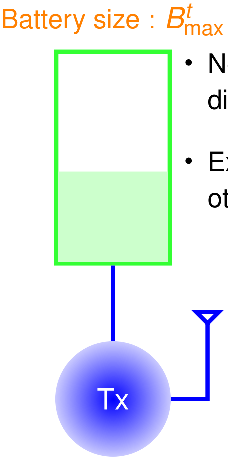

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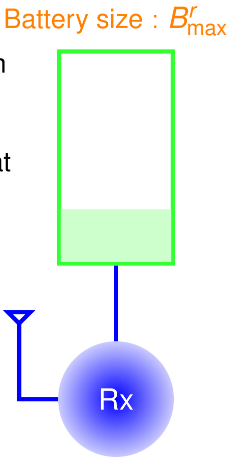
- Exact harvesting instants at other node are not known



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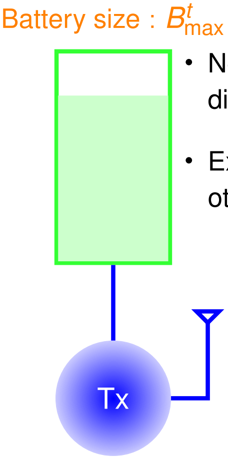

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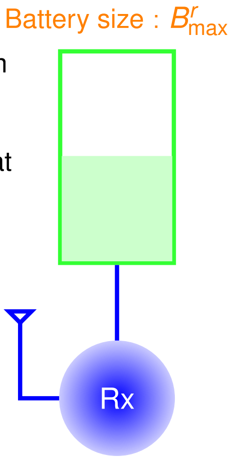

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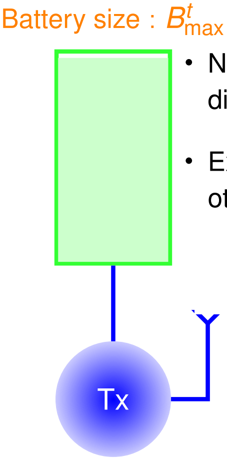

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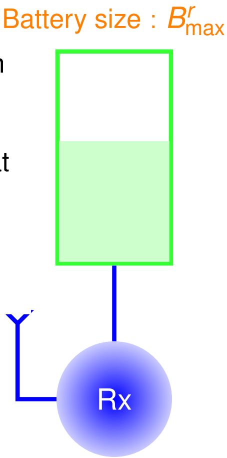

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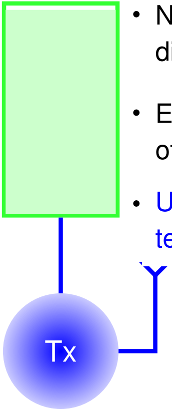
Battery size : $B^t_{\max}$



- Nodes harvest energy from distinct sources
- Exact harvesting instants at other node are not known
- Uncertainty about the battery state of the other node

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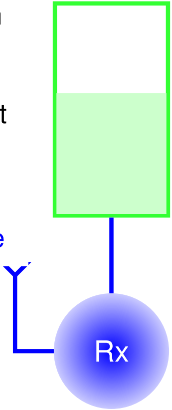
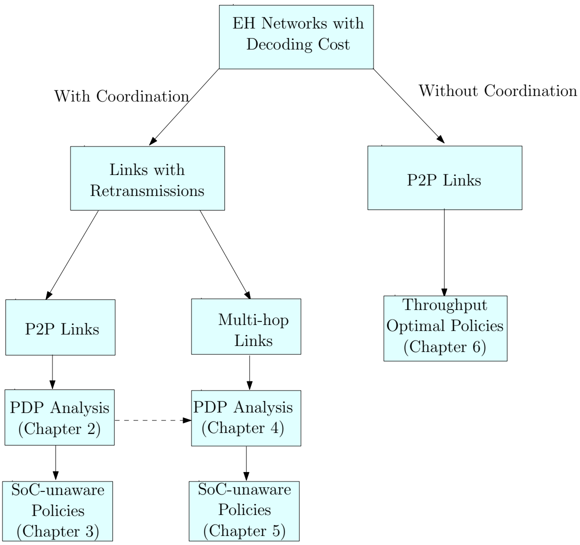


Thesis Layout



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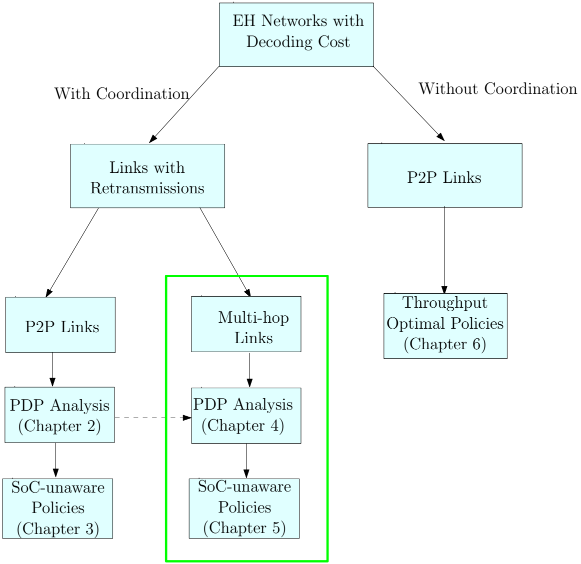

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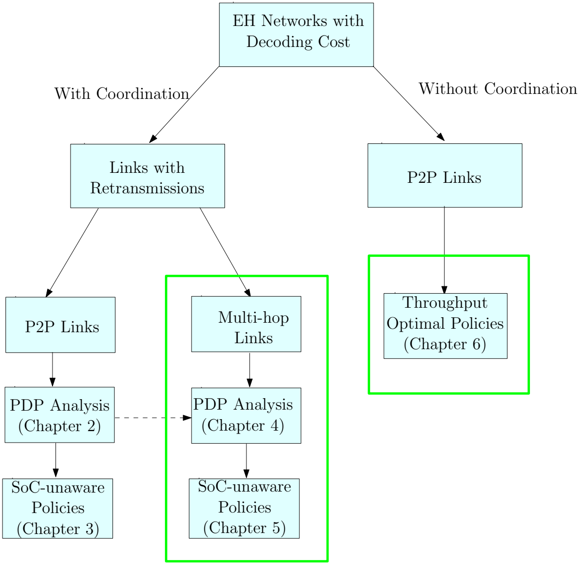


Publications

Journal Publications:

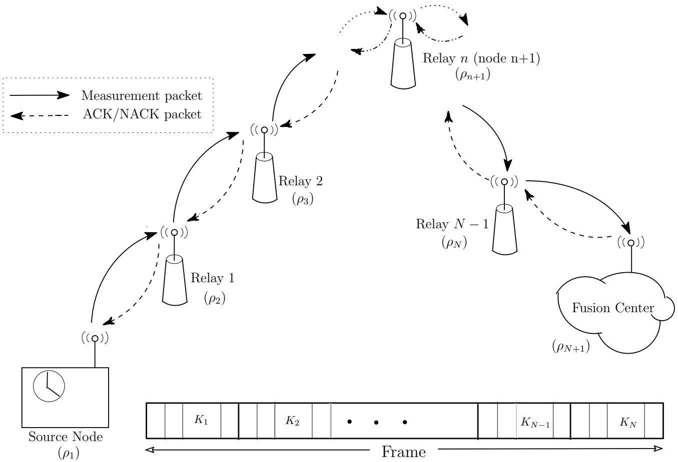
- M. Sharma and C. R. Murthy, “Packet Drop Probability Analysis of Dual Energy Harvesting Links with Retransmission,” *IEEE J. Sel. Areas in Commun.*, vol. 34, no. 12, pp. 3646 - 3660, Dec. 2016.
- M. Sharma and C. R. Murthy, “On Design of Dual Energy Harvesting Communication Links With Retransmission,” *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 4079 - 4093, Jun. 2017.
- M. Sharma and C. R. Murthy, “Distributed Power Control for Multi-hop Energy Harvesting Links with Retransmission,” to appear in *IEEE Trans. Wireless Commun.*, Mar. 2018.
- M. Sharma, C. R. Murthy and R. Vaze, “Asymptotically Optimal Uncoordinated Power Control Policies for Energy Harvesting Multiple Access Channels with Decoding Costs,” *submitted to IEEE Trans. Commun.*, Apr. 2018.

Conference Publications:

- M. Sharma and C. R. Murthy, “Packet Drop Probability Analysis of ARQ and HARQ-CC with Energy Harvesting Transmitters and Receivers,” *in Proc. IEEE GlobalSIP*, Dec. 2014, pp. 148-152.
- A. Devraj, M. Sharma and C. R. Murthy, “Power Allocation in Energy Harvesting Sensors with ARQ: A Convex Optimization Approach,” *in Proc. IEEE GlobalSIP*, Dec. 2014, pp. 208-212.
- M. Sharma, C. R. Murthy and R. Vaze, “On Distributed Power Control for Uncoordinated Dual Energy Harvesting Links: Performance Bounds and Near-Optimal Policies,” *in Proc. WiOpt*, May 2017.
- M. Sharma and C. R. Murthy, “Near-Optimal Distributed Power Control for ARQ Based Multihop Links with Decoding Costs,” *in Proc. IEEE ICC*, May 2017.

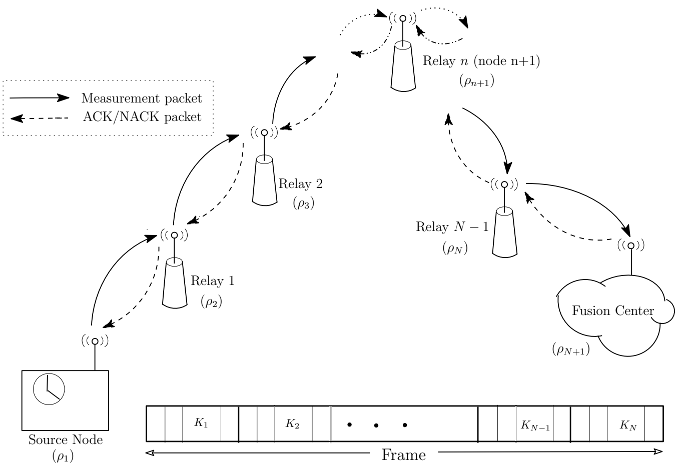
ARQ-based Multi-hop EH links

System Model



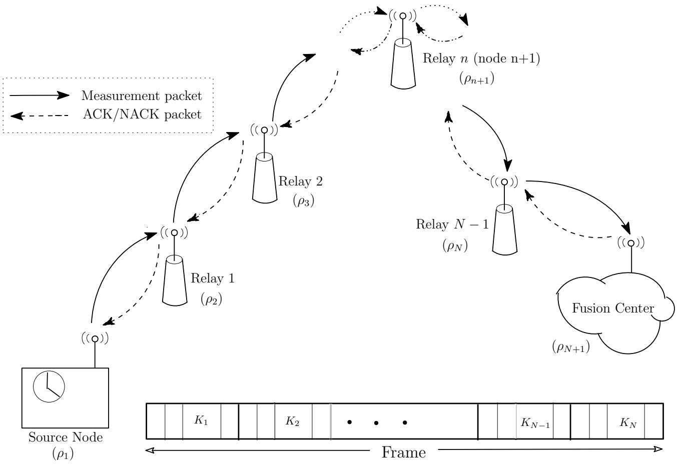
System Model

- Packet is generated at the start of the frame



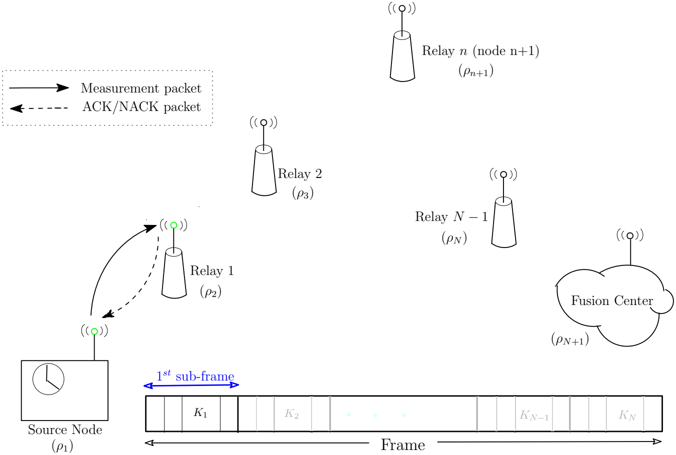
System Model

- Packet is generated at the start of the frame
- Dropped if not delivered by the end of the frame



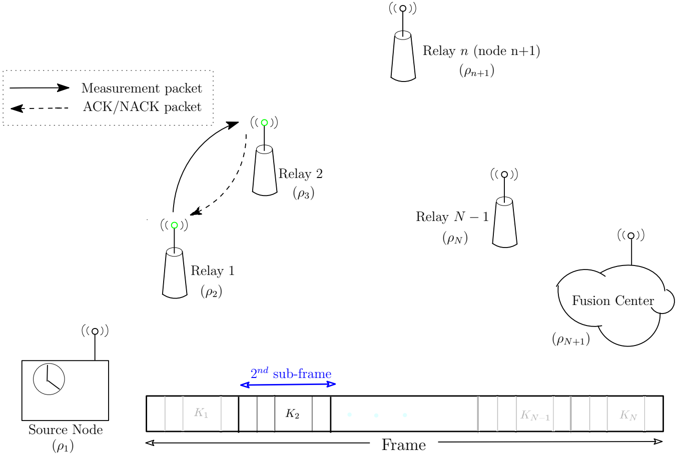
System Model

- Forwarded using half-duplex relays



System Model

- Forwarded using half-duplex relays
- Only n^{th} hop is active in the n^{th} sub-frame
  - Nodes harvest energy in all sub-frames



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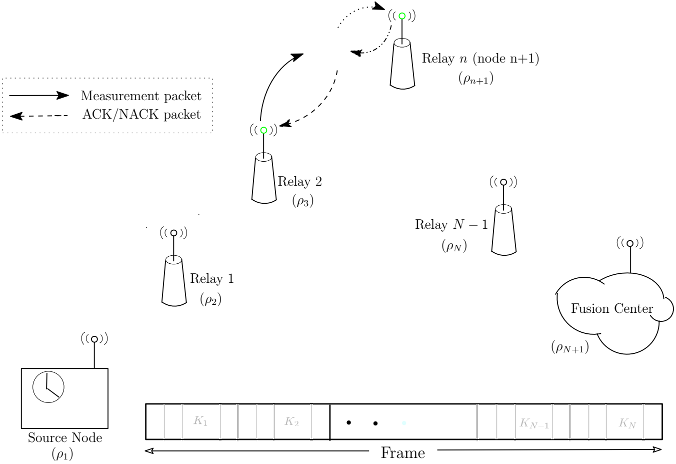

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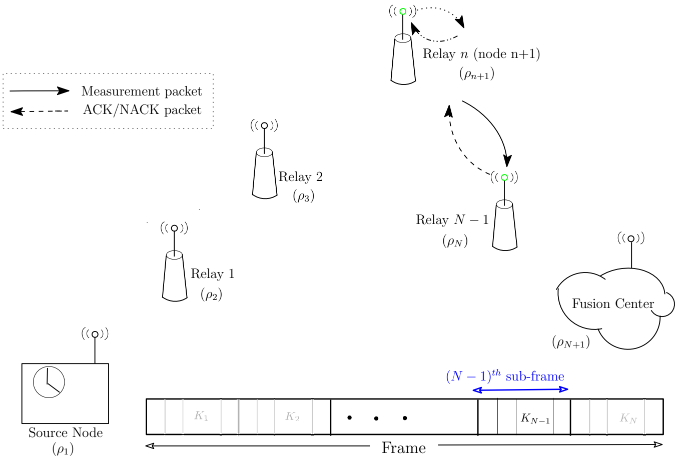
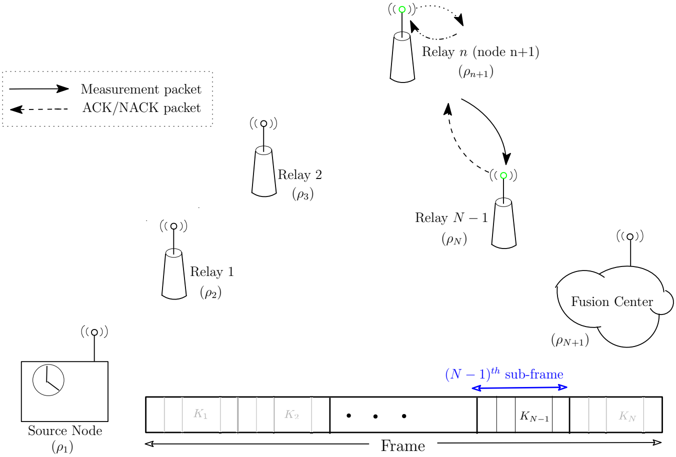
- Division of slots in sub-frames is fixed over time



System Model

- Division of slots in sub-frames is fixed over time
- Packet drop: transmission failed at intermediate hop



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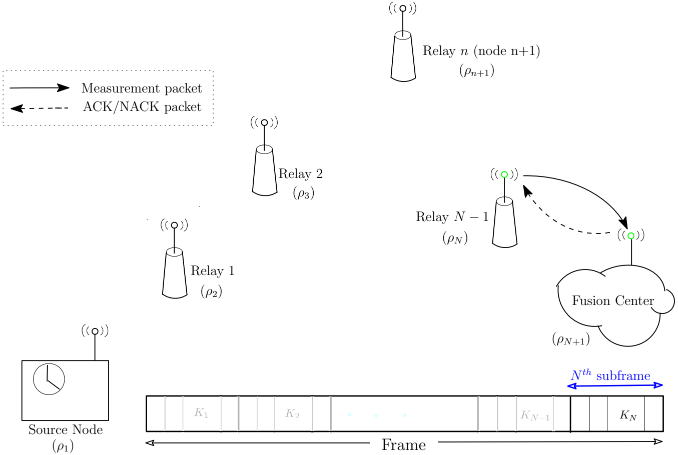
- Bernoulli energy harvesting model



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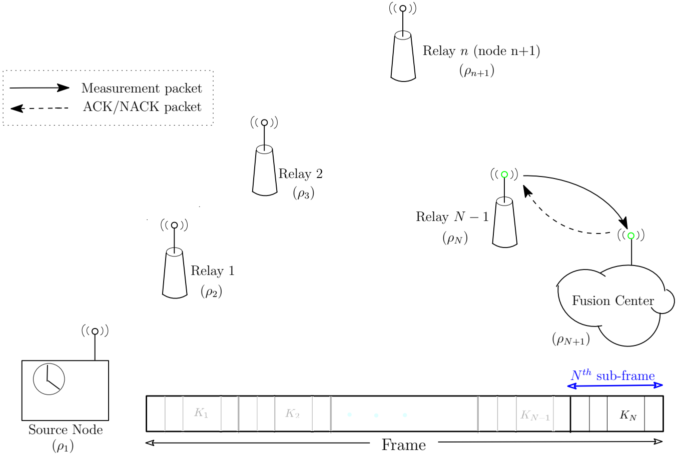
- Transmission at each hop follows the ARQ protocol



System Model: Coordinated Transmission between Two Successive Nodes

- After successful delivery Tx and Rx go to sleep:
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- Packet failure probability is

$$\text{P}_e(E_\ell^n, \gamma) = \exp\left(-\frac{E_\ell^n \gamma}{N_0}\right)$$

Goal & Contributions

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Contributions

- Closed-form expressions for packet drop probability
- Near-optimal distributed policies
  - For $R \approx 0$: closed-form expressions
  - For $R > 0$: iterative GP based solution
- Both slow and fast fading channels

Prior Work: Multi-hop EH links

1. Gatzianas et al. [TWC 2010], maximize the long-term rate
2. Lai et al. [TCOM 2016] use reliability as the metric
3. Mao et al. [TAC 2012], develop a near-optimal power and rate control policy to maximize long-term average sensing rate
4. Joseph et al. [ICUMTW 2009], propose joint power control, scheduling and routing scheme to maximize the throughput

System Evolution

- Modeled by the discrete-time Markov chain with state $(\boldsymbol{B}_s, \boldsymbol{U}_s, s)$[1]
- Battery Evolution at n^{th} Node:

$$B_{s+1}^n = \min\left(\left(B_s^n + \mathbb{1}_{\{\mathcal{H}_s^n\}} - E_\ell^n \mathbb{1}_{\{\mathcal{E}_{t,s}^n\}} - R\mathbb{1}_{\{\mathcal{E}_{r,s}^n\}}\right)^+, B_n^{\max}\right)$$

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- Local transmission index, U_s

$$U_s^n \triangleq \begin{cases} -1 & \text{ACK received,} \\ \ell & \ell - 1 \ \text{NACKs received, } \ell \in \{1, \ldots, K_n\}. \end{cases}$$

U_s^n is reset to zero at the start of the frame

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Packet Drop Probability

For a given set of policies $\mathcal{P} \triangleq \{\mathcal{P}^n\}_{n=1}^{N}$

$$P_{\mathrm{D}} = \sum_{\boldsymbol{B}} \pi(\boldsymbol{B}) \mathbb{E}_{\gamma} \left\{ P_D \left(K | \boldsymbol{B}, \boldsymbol{U} = \mathbf{1}, \gamma, s = 0 \right) \right\}$$

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- $\boldsymbol{\pi}$:stationary distribution of battery states at the start of the frame

$$\boldsymbol{\pi} = \left(\mathbb{E} \left[\boldsymbol{G}'(\gamma) \right] - \boldsymbol{I} + \boldsymbol{A} \right)^{-1} \mathbf{1}$$

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$\boldsymbol{G'}(\gamma)$ is the K-step TPM with entries

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$$\Pr \left[\boldsymbol{B}_{(M+1)K} = \boldsymbol{B}_2 | \boldsymbol{B}_{MK} = \boldsymbol{B}_1, \gamma \right]$$

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- Conditional PDP can be found in closed-form

PDP Minimization & Bounds

$$\min_{\{\mathcal{P}^n\}_{n=1}^N} P_\text{D} = \min_{\{\mathcal{P}^n\}_{n=1}^N} \sum_{\boldsymbol{B}} \pi(\boldsymbol{B}) \mathbb{E}_\gamma \left\{ P_D \left(K | \boldsymbol{B}, \boldsymbol{U} = \boldsymbol{1}, \gamma \right) \right\},$$

subject to: $0 \leq E_\ell^n \leq E_\text{max}$ for all $1 \leq \ell \leq K_n$ and $1 \leq n \leq N$.

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Difficult to Solve!

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Bounds:

For a multi-hop EH link operating using policies $\mathcal{P}$,

$$P^*_{\mathrm{D}_\infty} \leq \min_{\{\mathcal{P}^n\}_{n=1}^N} P_{\mathrm{D}} \leq P^*_{\mathrm{D}_\infty} + \sum_{\boldsymbol{B} \in \mathcal{I}_A^c} \pi(\boldsymbol{B}) \Big|_{\mathcal{P}^*}$$

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$$\min_{\{\mathcal{P}^n\}_{n=1}^N} P_\text{D} \quad = \min_{\{\mathcal{P}^n\}_{n=1}^N} \sum_{\boldsymbol{B}} \pi(\boldsymbol{B}) \mathbb{E}_\gamma \left\{ P_D\left(K | \boldsymbol{B}, \boldsymbol{U} = \boldsymbol{1}, \gamma\right)\right\},$$

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For a multi-hop EH link operating using policies $\mathcal{P}$,

$$P_{\text{D}_\infty}^* \leq \min_{\{\mathcal{P}^n\}_{n=1}^N} P_\text{D} \leq P_{\text{D}_\infty}^* + \sum_{\boldsymbol{B} \in \mathcal{I}_A^c} \pi(\boldsymbol{B}) \Big|_{\mathcal{P}^*}$$

$P_{\text{D}_\infty}^* \triangleq \min_{\{\mathcal{P}^n\}_{n=1}^N} \mathbb{E}_\gamma \left\{ P_\text{D}\left(K | \cdot\right)\right\}$ and $\mathcal{P}^* \triangleq \arg \min_{\{\mathcal{P}^n\}_{n=1}^N} \mathbb{E}_\gamma \left\{ P_\text{D}\left(K | \cdot\right)\right\}$ for any $\boldsymbol{B} \in \mathcal{I}_A$, the set of "GOOD" battery states.

Tightness of the Bounds

- Lower bound: Optimum PDP under average power constraint, with infinite battery[2]
- Difference between lower and upper bound: upper bound on the penalty due to finite batteries under the EUR

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Theorem (MSharma-TWC-June2017)

For a multi-hop EH link operating under EUR

$$\sum_{\boldsymbol{B} \in \mathcal{I}_A^c} \pi(\boldsymbol{B}) = \sum_{n=1}^{N+1} \Theta(e^{r_n^* B_n^{\max}})$$

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- Large battery regime: use lower bound as objective and replace ENC by EUR constraints

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Reformulation

$$\max_{\{\mathcal{P}^n\}_{n=1}^N} \Pr[N+1]$$
$$\text{subject to } \bar{T}_n + \bar{R}_n \leq K\rho_n,$$
$$0 \leq E_\ell^n \leq E_{\max},$$

Reformulation

Probability that packet reaches destination

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Nonconvex mixed integer program with 2^K subproblems

Reformulation: Negligible Cost of Reception

$$
\begin{aligned}
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\text{subject to} \quad & \bar{T}_n + \cancelto{0}{\bar{R}_n} \leq K\rho_n, \\
& 0 \leq E_\ell^n \leq E_{\max},
\end{aligned}
$$

$$
\Pr[n] = \prod_{m=1}^{n-1} \left(1 - \frac{1}{1 + \sum_{\ell=1}^{K_m} E_\ell^m} \right)
$$

$$
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$$

$$
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$$

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- Optimal policy obtained using the solution for P2P links

Optimal Policy without Peak Power Constraint

Theorem: slow fading

The unique optimal policy for n^{th}-hop is given by

$$E_k^{n*} = \frac{\rho_n K}{K_n \Pr[n]} \left(1 + \frac{\rho_n K}{K_n N_0 \Pr[n]}\right)^{k-1}, \; k = 1, 2, \ldots, K_n.$$

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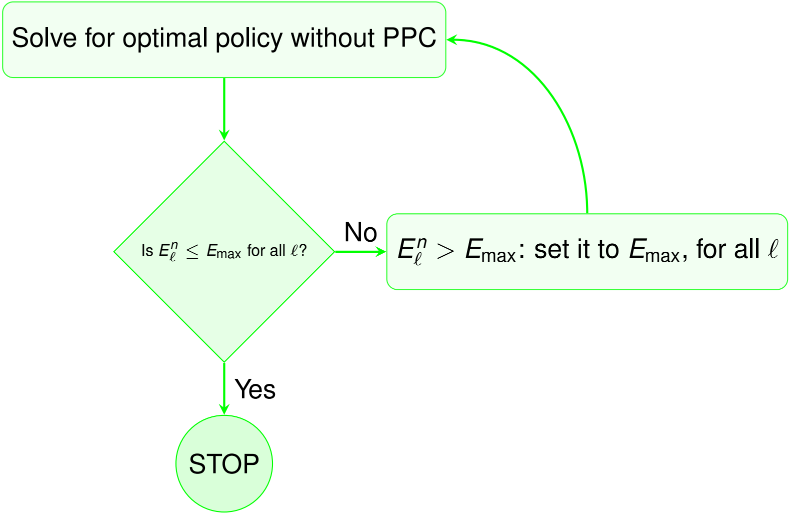
Theorem: fast fading

The successive power levels of the optimal policy at n^{th}-hop satisfies

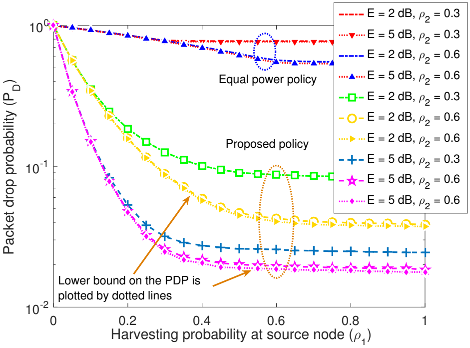
$$E_{\ell+1}^{n^*} = \frac{E_\ell^{n^*}(E_\ell^{n^*} + 2)}{2},$$

for all $1 \leq \ell \leq K_n$.

Optimal Policy with Peak Power Constraint



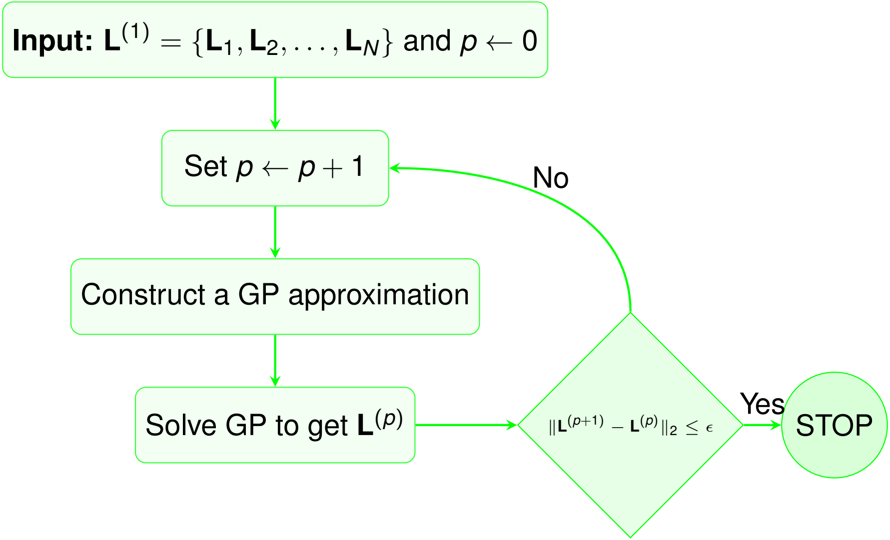
Performance of the Closed-form Policy



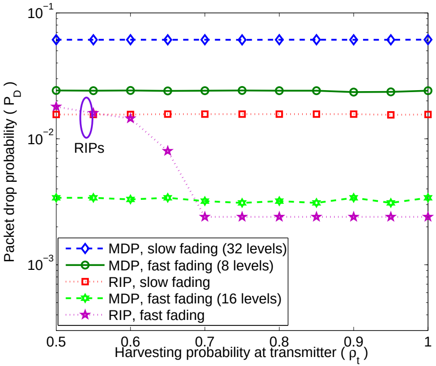
No. of hops = 2
$E_{\max} = 10E_s$
$K_1 = K_2 = 4$

The policy obtained using proposed approach achieves the lower bound and outperforms the EPP $[E_{\max}\ E_{\max}\ E_{\max}\ E_{\max}]$.

General Case: Integer Constraints ($2^K \to \prod_{n=1}^{N} K_n$) & Solving CGP



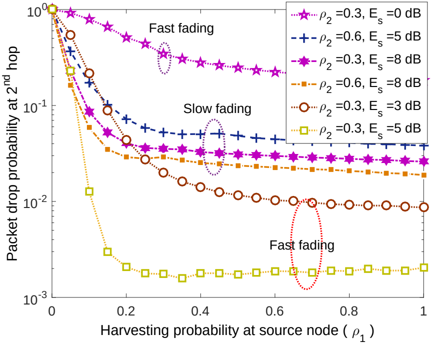
RIPs Vs MDP based policy



No. of hops = 1
$R = 1$
$E_{max} = 4E_s$ and $2E_s$
$K_1 = 4$

For slow fading channels, the RIP uniformly outperforms the MDP, while in the fast fading case, for $\rho_t > 0.7$, the RIP outperforms the corresponding MDP based policies.

PDP at 2^{nd} Hop



No. of hops = 2
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PDP at the second hop improves with increase in the harvesting rate at the source node.

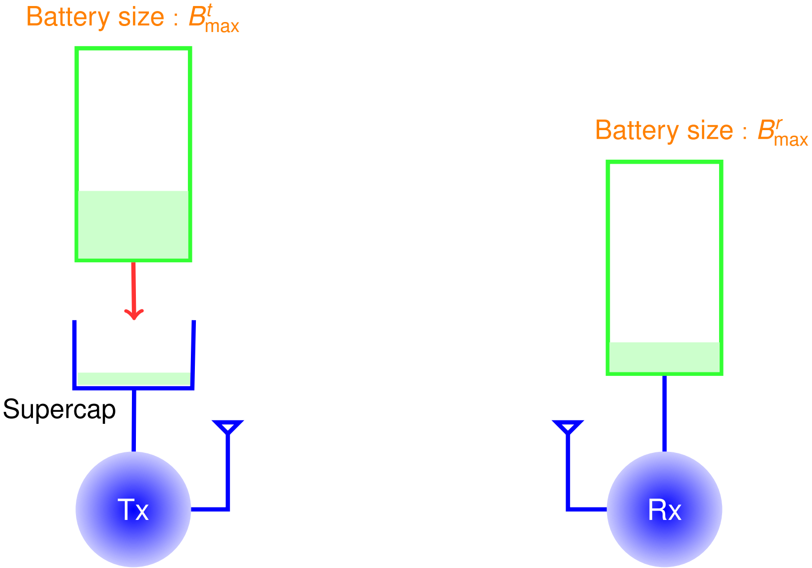
Summary

- Presented closed-form expressions for the PDP
- Characterized the dependence of the PDP on size of the batteries
  - Can design policies under EUR if battery capacity is sufficiently large
- Obtained closed-form expressions for near-optimal RIPs when $R \approx 0$
- Near optimal policies when $R > 0$
- The proposed policy outperforms the EPP and MDP based policies

Uncoordinated Dual EH Links

(Joint work with Prof. Rahul Vaze, TIFR)

System Model



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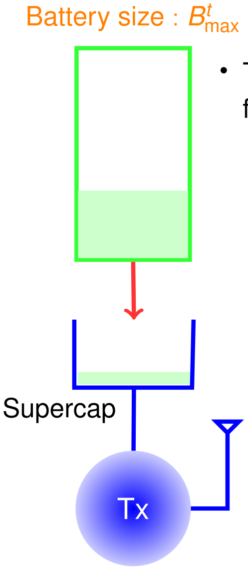
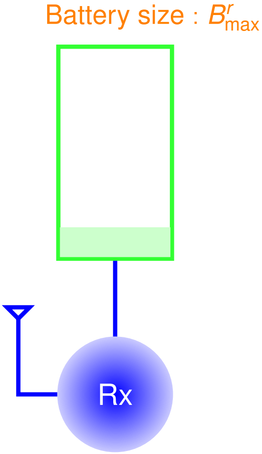


- Transmit energy is transferred to super-capacitor



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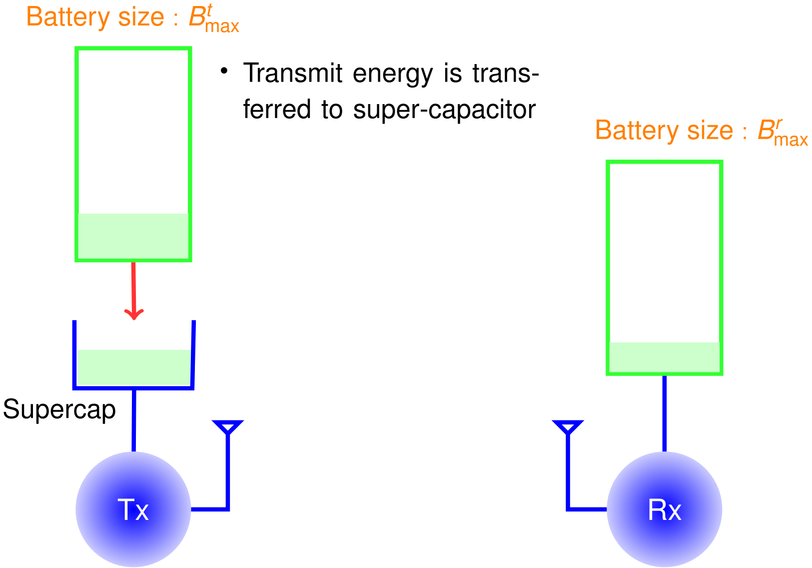

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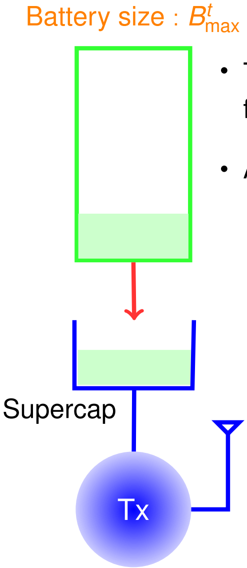

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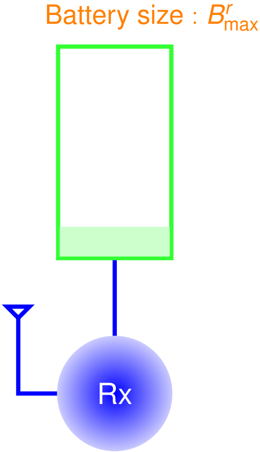

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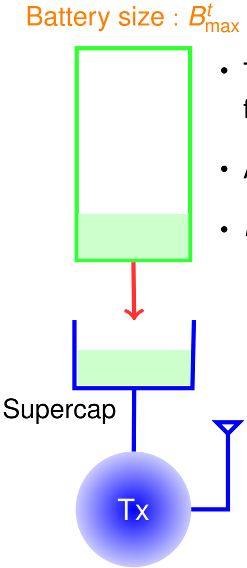

- Transmit energy is transferred to super-capacitor
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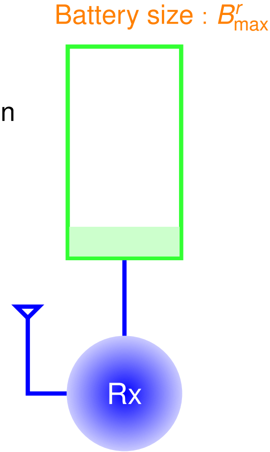

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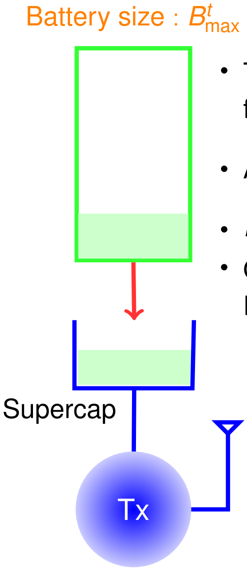

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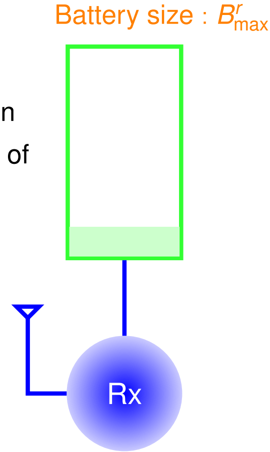
- Only mean and variance of EH process are known



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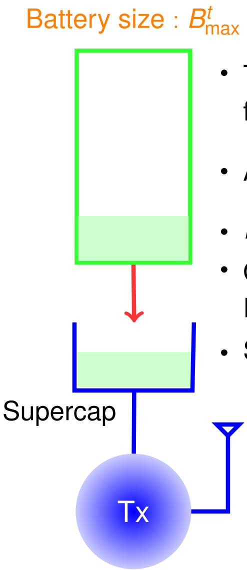

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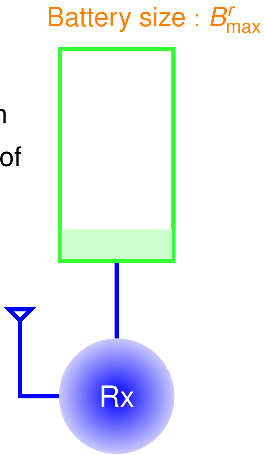

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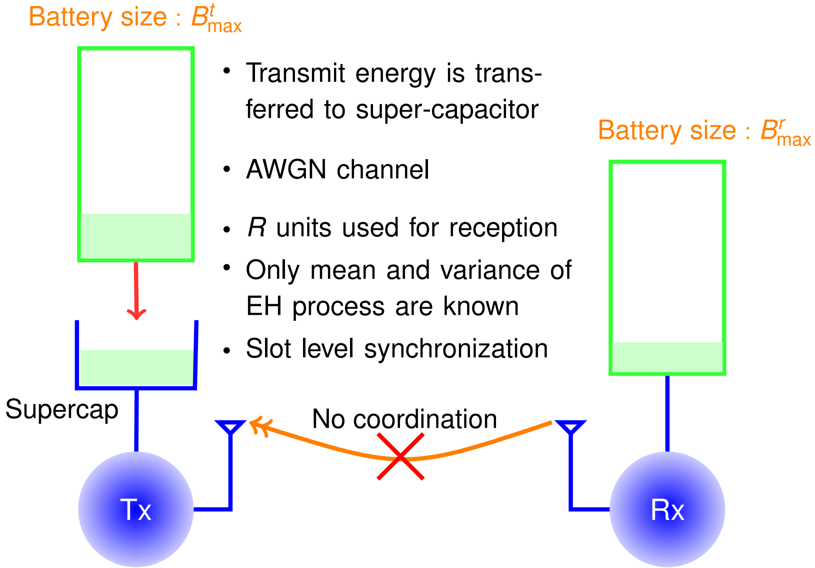
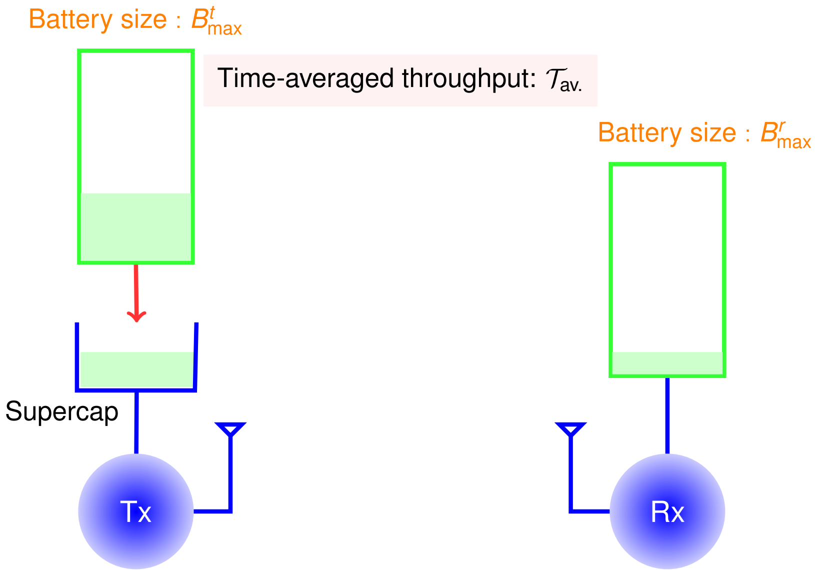


Prior Work: Dual EH Links

1. Arafa and Ulukus [JSAC 2015], maximize the coordinated throughput
   - Non-causal knowledge of energy arrivals at both nodes
2. Zhou et al. [JSAC 2015] consider retransmission-based dual EH links
   - Coordinated sleep-wake protocol
3. Sharma and Murthy [TWC 2017], optimize packet drop probability of retransmission-based dual EH links
   - Use ACK/NACK messages to achieve perfect coordination
   - One bit feedback facilitates coordination
4. Doshi and Vaze [ICSS 2014], analyze throughput of uncoordinated links with unit sized batteries

Impact of Uncoordination



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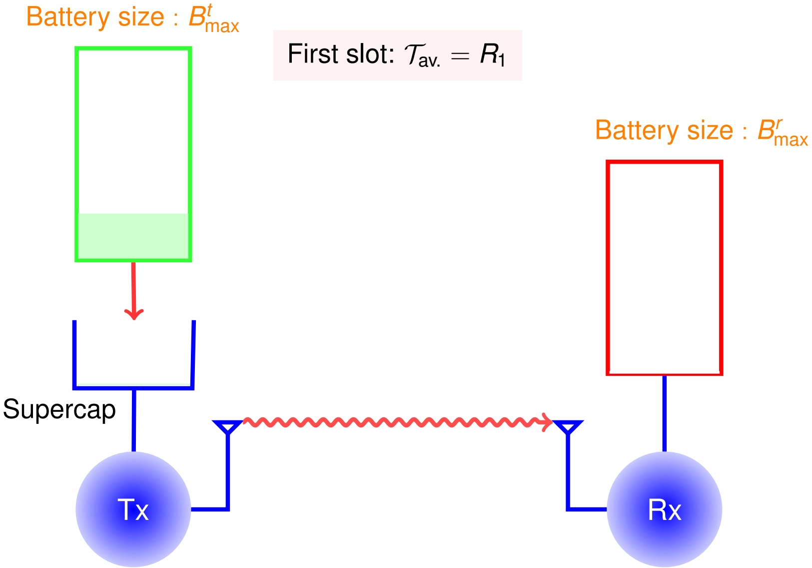

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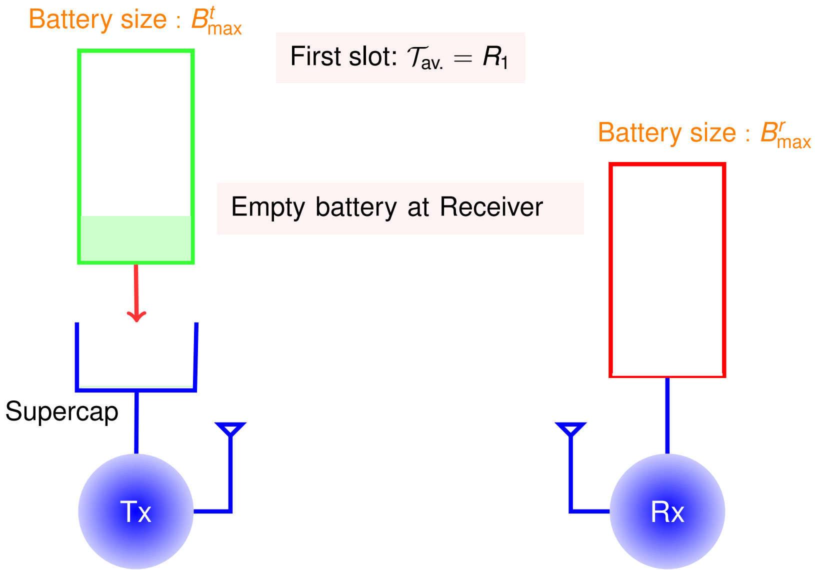

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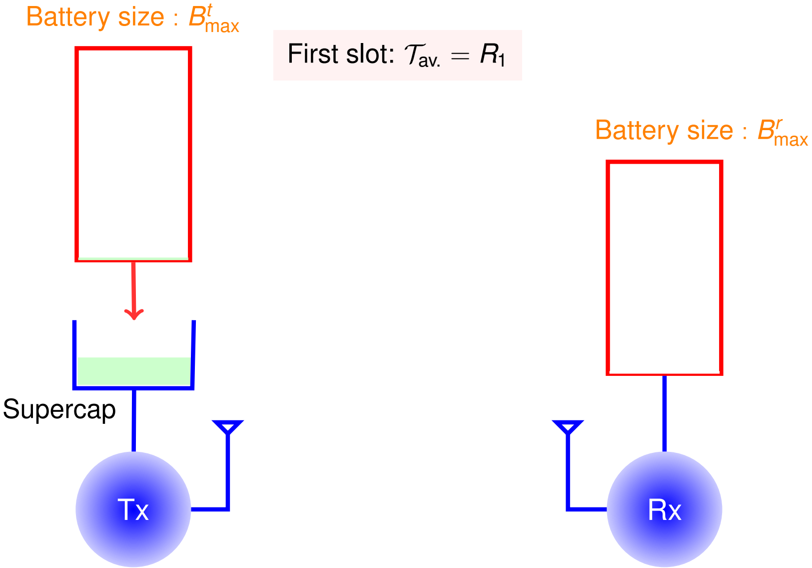

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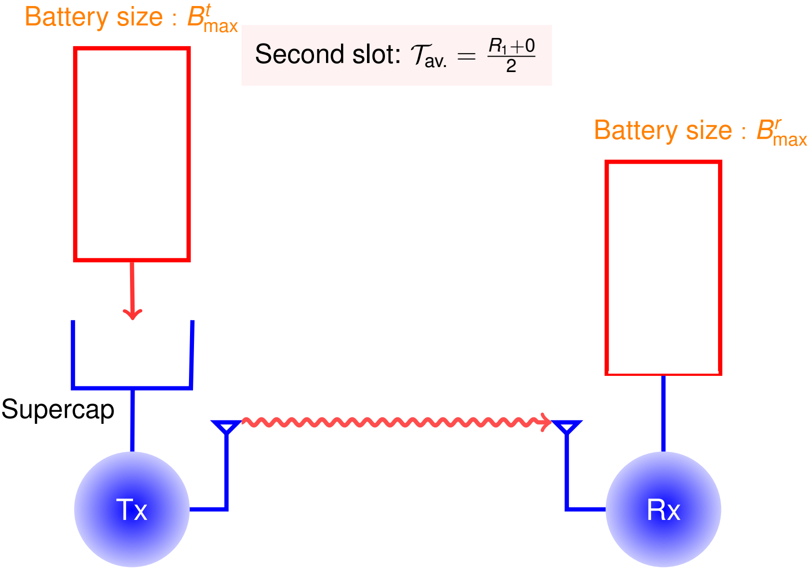
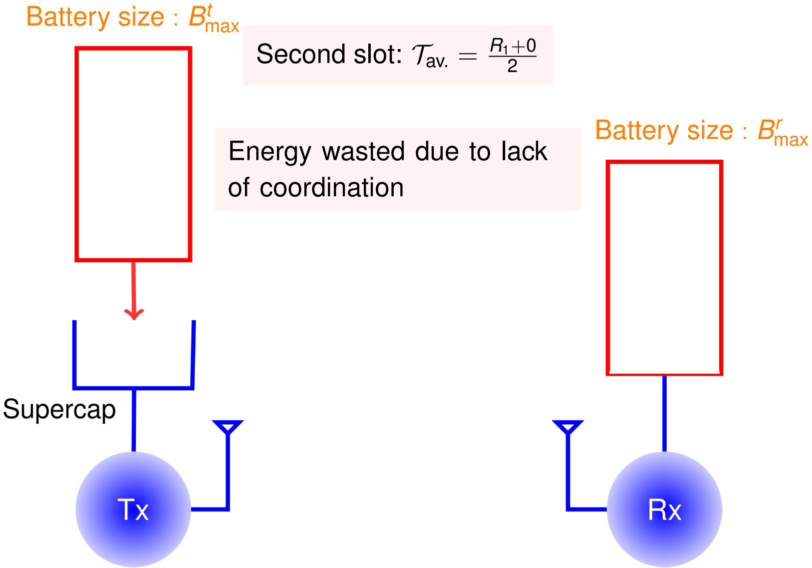


Impact of Uncoordination

Second slot: $\mathcal{T}_{av.} = \frac{R_1+0}{2}$

Energy wasted due to lack of coordination



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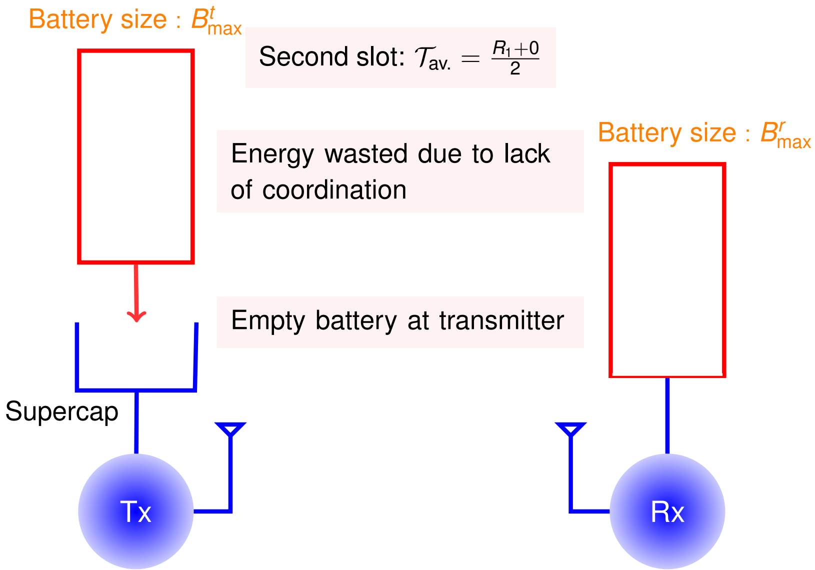

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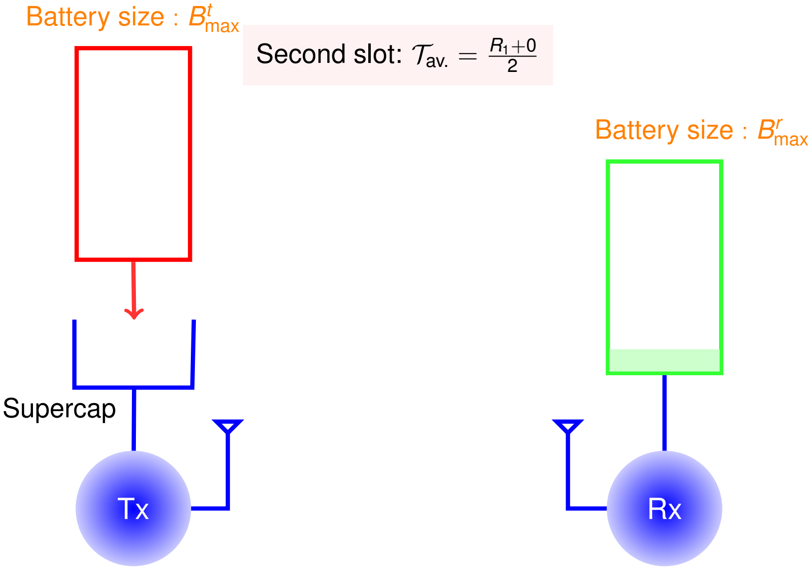

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Third slot: $\mathcal{T}_{av.} = \frac{R_1+0+0}{3}$

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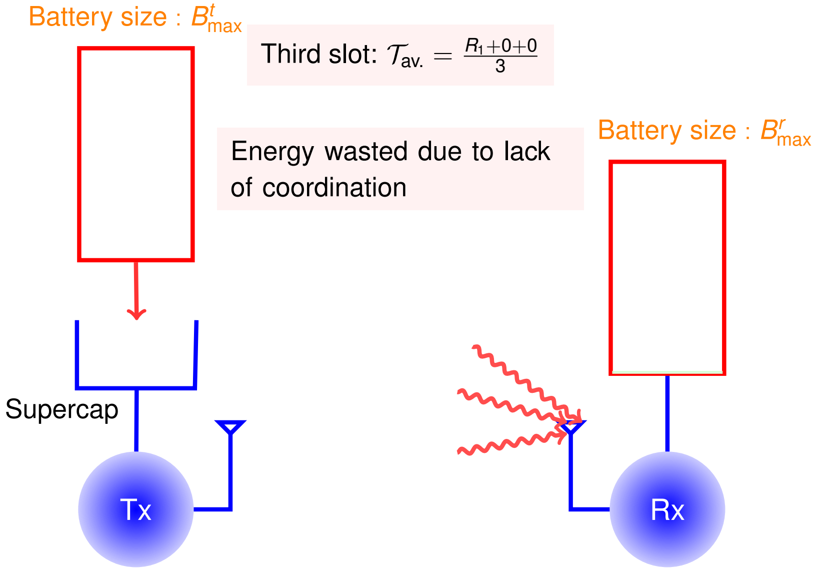
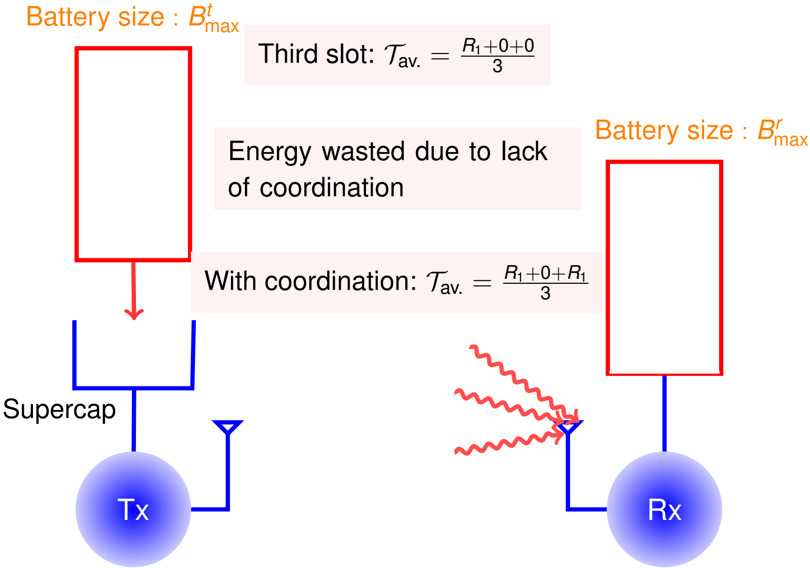


Impact of Uncoordination

Third slot: $\mathcal{T}_{\text{av.}} = \frac{R_1+0+0}{3}$

Energy wasted due to lack of coordination

With coordination: $\mathcal{T}_{\text{av.}} = \frac{R_1+0+R_1}{3}$



Goal & Contributions

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2. Design a policy that achieves optimal throughput

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1. Upper-bound on the throughput
2. Asymptotically optimal policies
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2. Asymptotically optimal policies
   - Energy unconstrained receiver ($\mu_r \geq R$)
   - Energy constrained receiver ($\mu_r < R$)
     - Policy with *occasional* one bit feedback from receiver
     - Policy with time-dilation at receiver: asymptotically no feedback
     - Fully uncoordinated policy

Mathematical Formulation

Objective:

$$\max_{\substack{p_t(n),\\ p_r(n), n \geq 1}} \lim_{N \to \infty} \frac{1}{N} \sum_{n=1}^{N} \mathbb{1}_{\{p_r(n) \neq 0\}} \log(1 + p_t(n))$$

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Policy at Tx and Rx

zero if receiver is off

Constraints:

1. Energy used by a node can not exceed the energy in its battery, i.e.,

$$B^t_{n+1} = \min\left\{\max\{0, B^t_n + \mathcal{E}_t(n) - p_t(n)\}, B^t_{\max}\right\}$$

2. Receiver can consume either 0 or R units of energy

Upper Bound

Lemma

The long-term time-averaged throughput of a dual EH link satisfies:

$$\mathcal{T} \leq \begin{cases} \log\left(1 + \mu_t\right) & \text{if } \mu_r > R, \\ \left(\frac{\mu_r}{R}\right) \log\left(1 + \frac{R\mu_t}{\mu_r}\right) & \text{if } \mu_r \leq R \end{cases}$$

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μ_t and μ_r: rate of harvesting at the transmitter and receiver

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The long-term time-averaged throughput of a dual EH link satisfies:

Equivalent to when only Tx is EHN

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where $\mathcal{T} \triangleq \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} \mathbb{1}_{\{p_r(n)\neq 0\}} \log(1+p_t(n))$

μ_t and μ_r: rate of harvesting at the transmitter and receiver

Proof Sketch

Unconstrained Receiver: $\mu_r > R$

$$
\begin{aligned}
\mathcal{T} &\leq \lim_{N\to\infty} \frac{1}{N} \sum_{n=1}^{N} \log(1 + p_t(n)) \\
&= \mathbb{E}\left\{\log(1 + p_t(n))\right\} \leq \log(1 + \mathbb{E}\left[p_t(n)\right]) \\
&\leq \log(1 + \mu_t)
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$$

Constrained Receiver: $\mu_r < R$

1. A genie-aided system which has non-causal information about energy arrivals at both the nodes
2. Number of slots receiver can be on $= \frac{N\mu_r}{R}$
3. Transmitter uses equal power $p_t(n) = \frac{R\mu_t}{\mu_r}$ across these slots
4. $\mathcal{T} \leq \left(\frac{\mu_r}{R}\right) \log\left(1 + \frac{R\mu_t}{\mu_r}\right)$

Proof Sketch

Unconstrained Receiver: $\mu_r > R$

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$$= \mathbb{E}\left\{\log(1 + p_t(n))\right\} \leq \log(1 + \mathbb{E}[p_t(n)])$$
$$\leq \log(1 + \mu_t)$$

$\frac{R}{\mu_r}$ is time taken to harvest R units of energy

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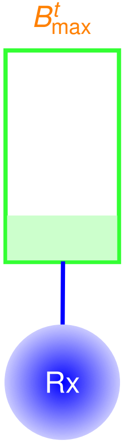
Optimal Policy: Energy Unconstrained Receiver

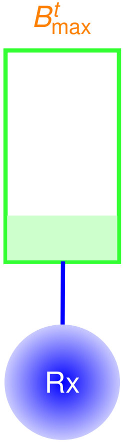
- Receiver remains ON in every slot



Optimal Policy: Energy Unconstrained Receiver

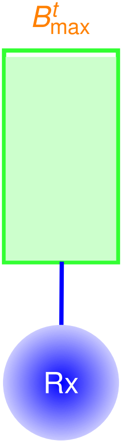
- Receiver remains ON in every slot

- Since $\mu_r > R$, harvesting rate is more than the energy required for receiving the data



Optimal Policy: Energy Unconstrained Receiver

- Receiver remains ON in every slot
- Since $\mu_r > R$, harvesting rate is more than the energy required for receiving the data
- Probability that receiver runs out of energy decays exponentially with receiver battery size
- Equivalent to the Tx-only EHN case



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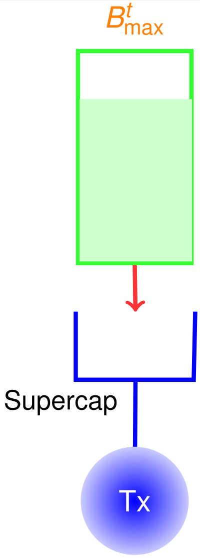

[1] R. Srivastava and C. E. Koksal, ***Basic performance limits and tradeoffs in energy-harvesting sensor nodes with finite data and energy storage***, **IEEE/ACM Trans. Netw., vol. 21, pp. 1049-1062, Aug. 2013.**

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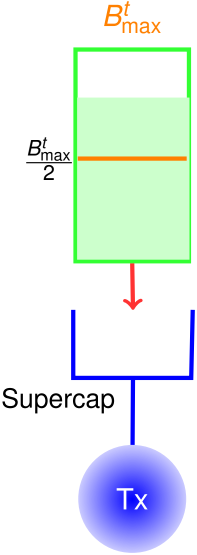

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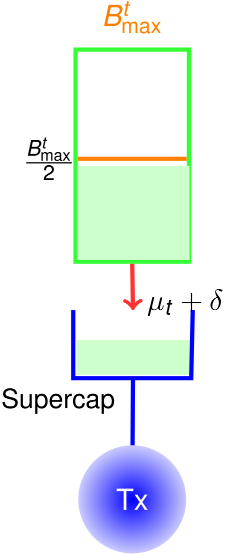

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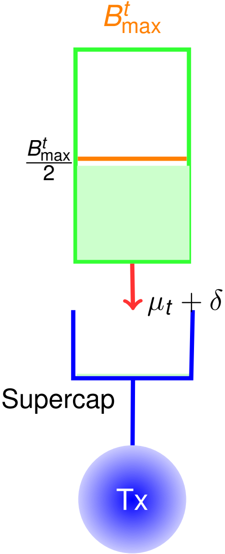

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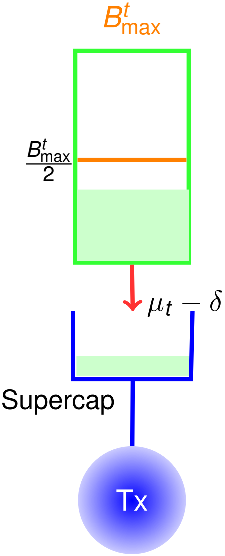

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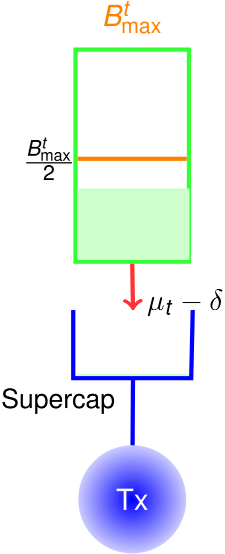

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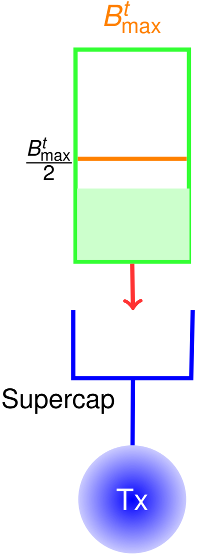

$$p_t(n) = \begin{cases} \mu_t + \delta & \text{if} \quad B_n^t \geq \frac{B_{\max}^t}{2} \\ \min\{B_n^t, \mu_t - \delta\} & \text{if} \quad B_n^t < \frac{B_{\max}^t}{2} \end{cases}$$

- $\delta = \beta_t \sigma_t^2 \frac{\log B_{\max}^t}{B_{\max}^t}$, where β is a constant[1]

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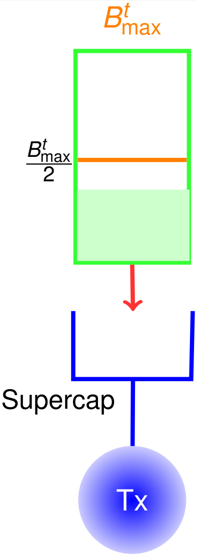

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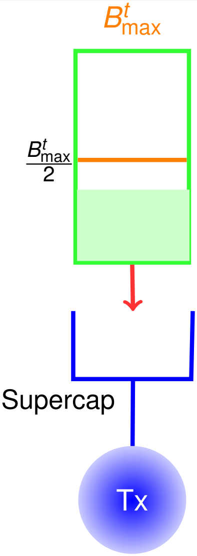

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- $\delta = \beta_t \sigma_t^2 \frac{\log B^t_{max}}{B^t_{max}}$, where β is a constant[1]
- Throughput achieved by policy converges to upper bound at rate $\Theta\left(\left(\frac{\log B^t_{max}}{B^t_{max}}\right)^2\right)$
- Fully uncoordinated policy!

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Performance: Policy for Unconstrained Receiver

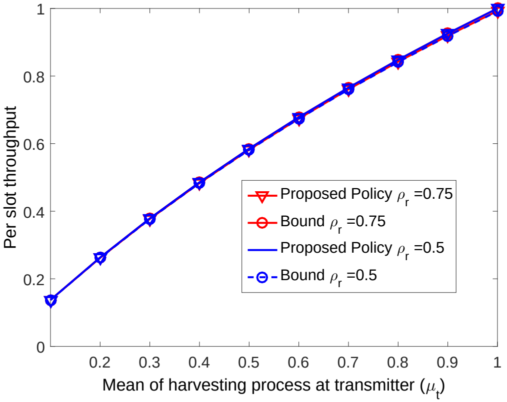
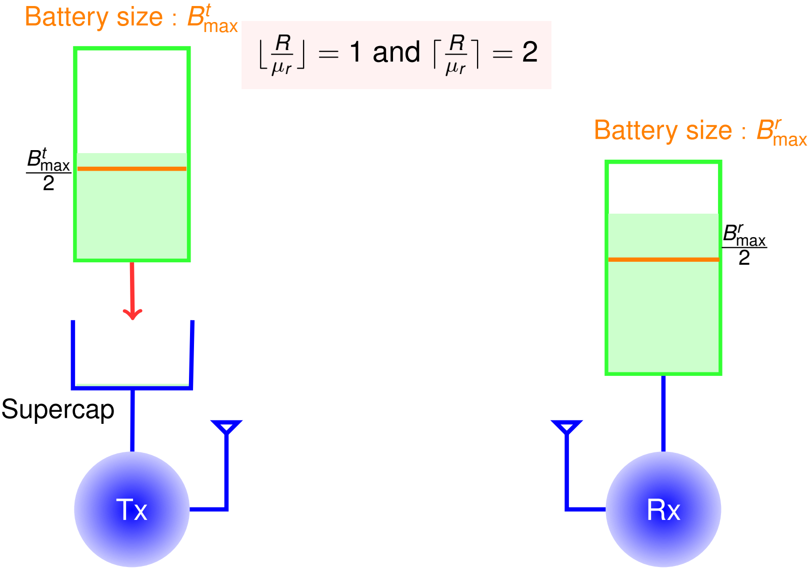


Figure: Parameters: $R = 0.5$ and $B^t_{\text{max}} = B^r_{\text{max}} = 50$.

Optimal Policy Example: $R = 1.25\mu_r$

$\left\lfloor \frac{R}{\mu_r} \right\rfloor = 1$ and $\left\lceil \frac{R}{\mu_r} \right\rceil = 2$



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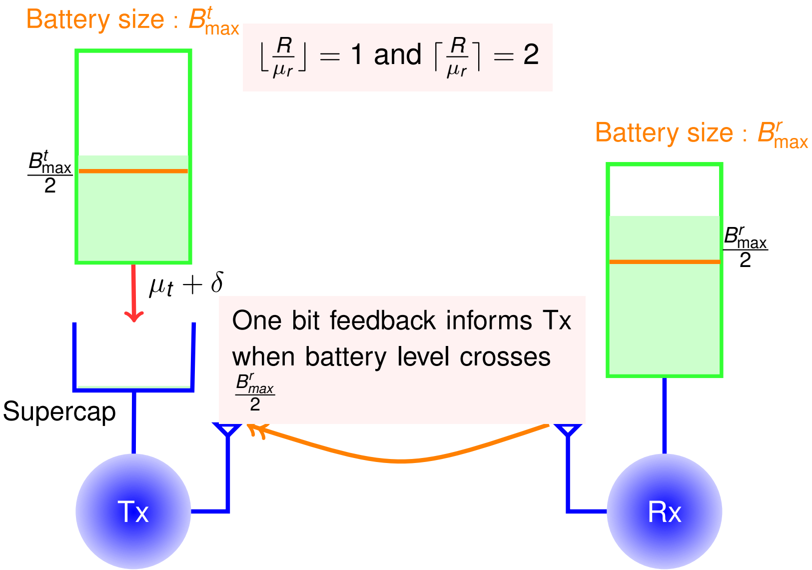

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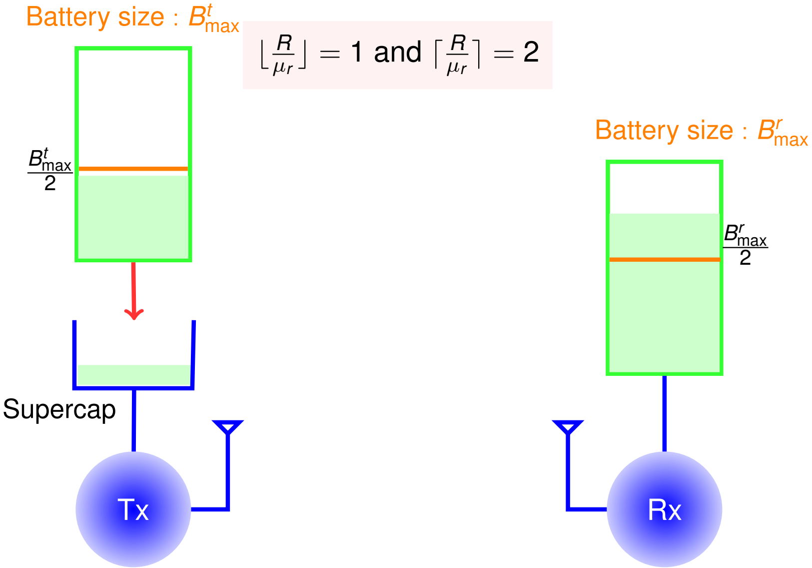

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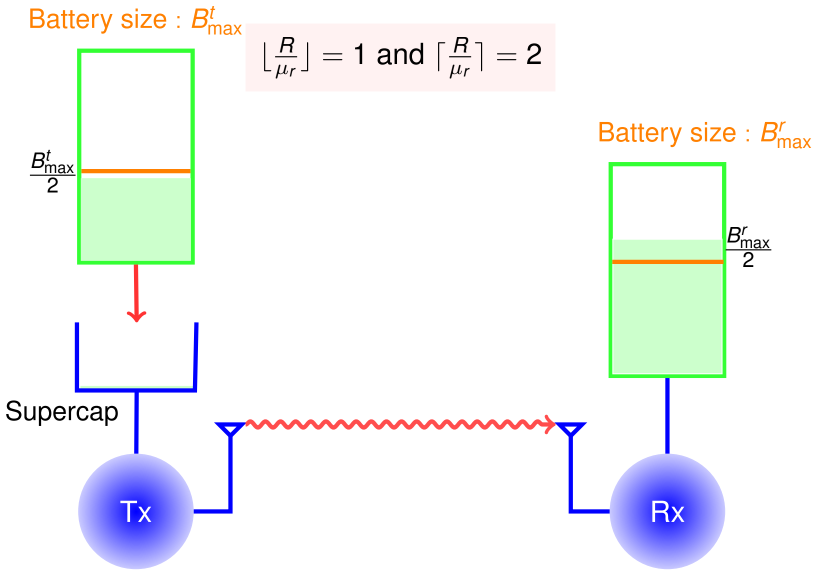

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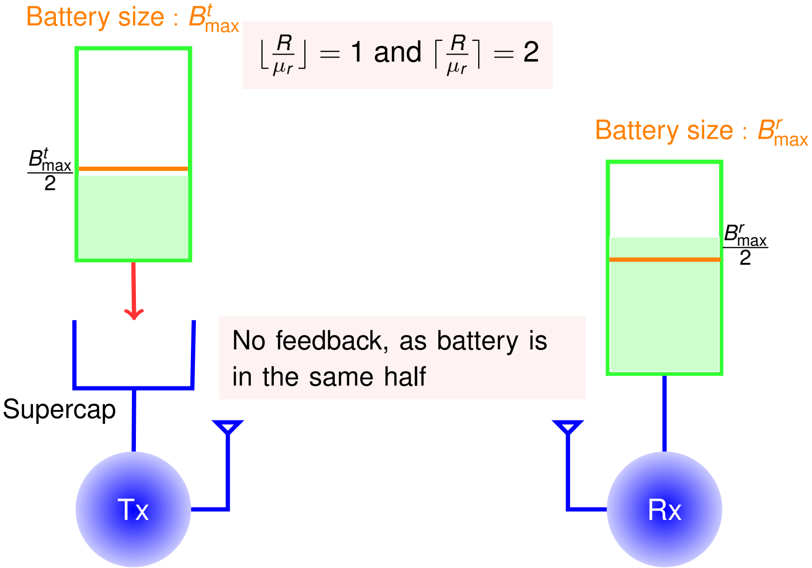

No feedback, as battery is in the same half

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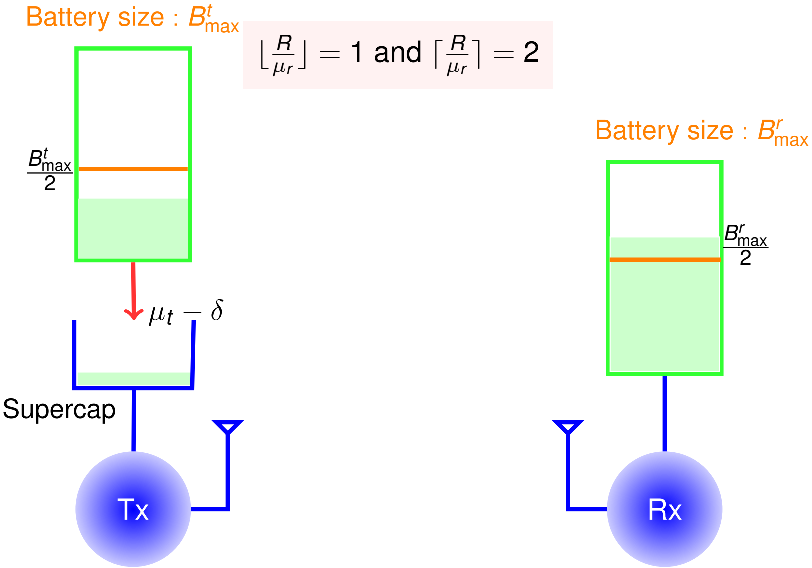

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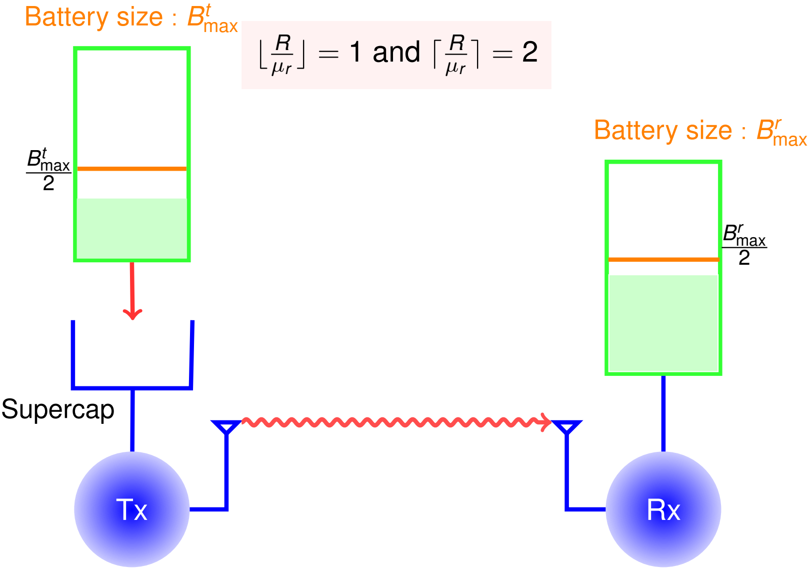

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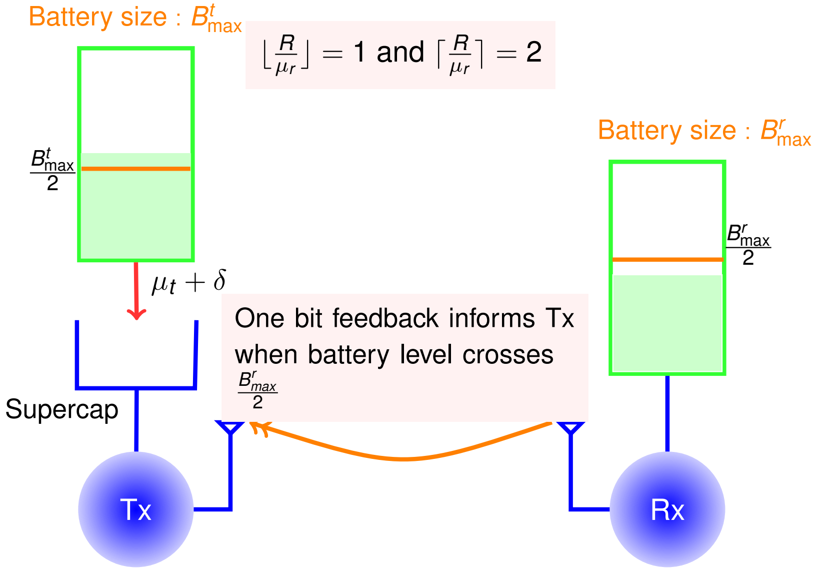

One bit feedback informs Tx when battery level crosses $\frac{B^r_{max}}{2}$

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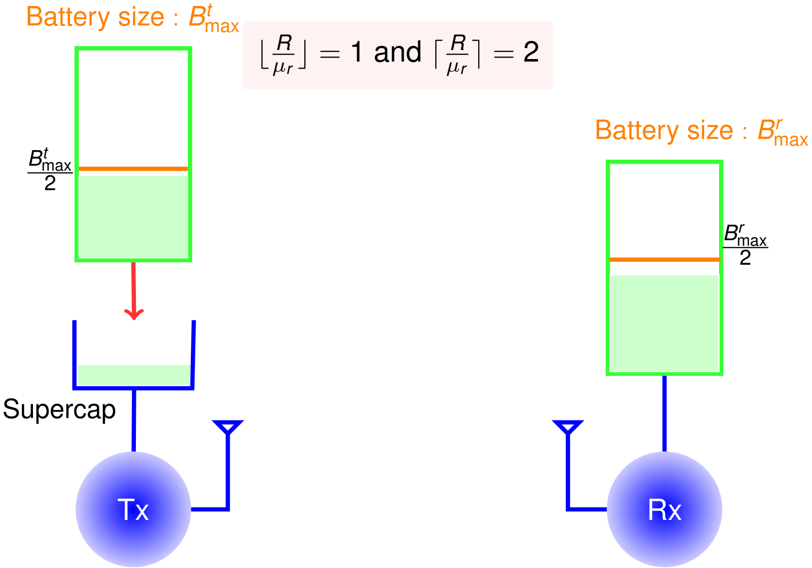

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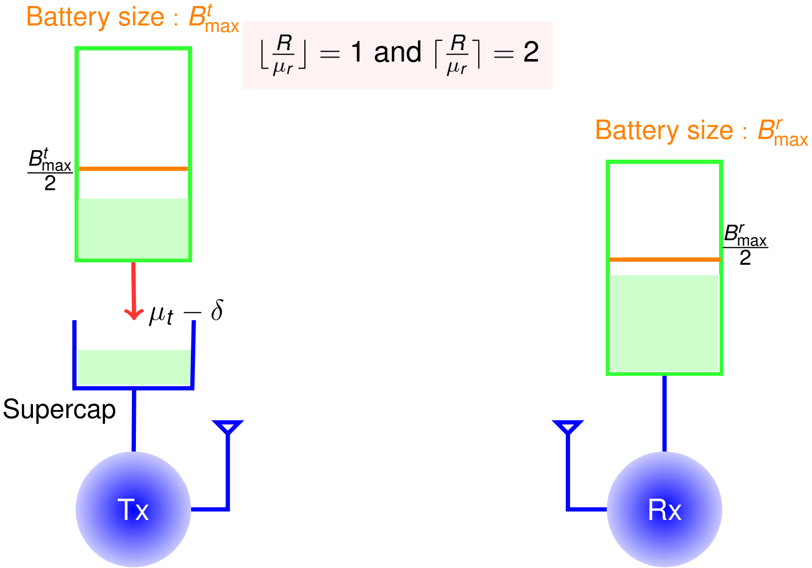

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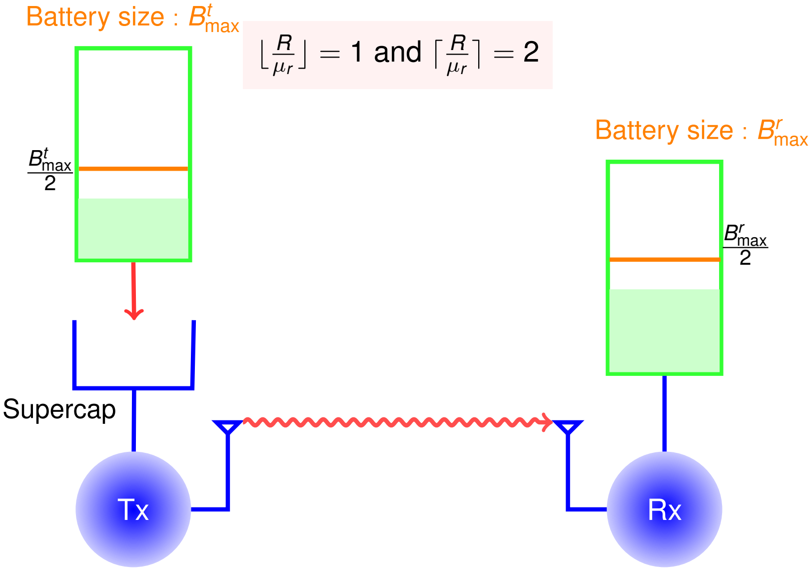

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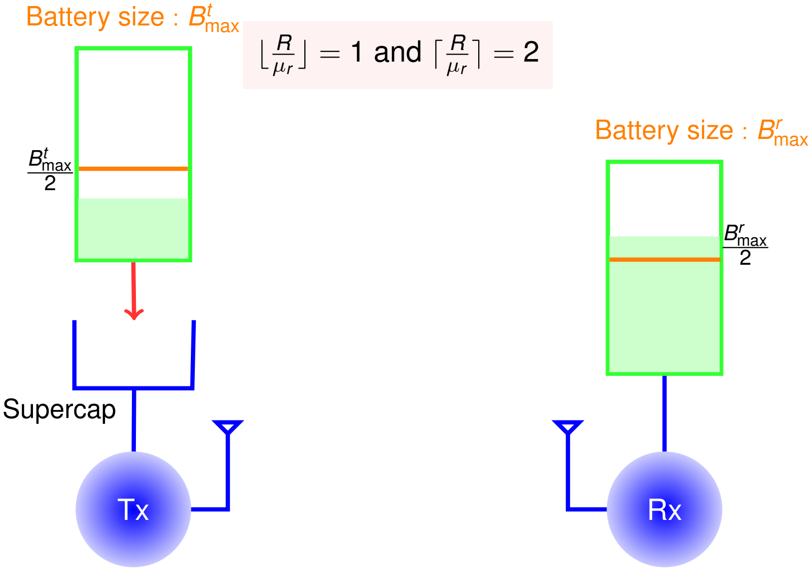

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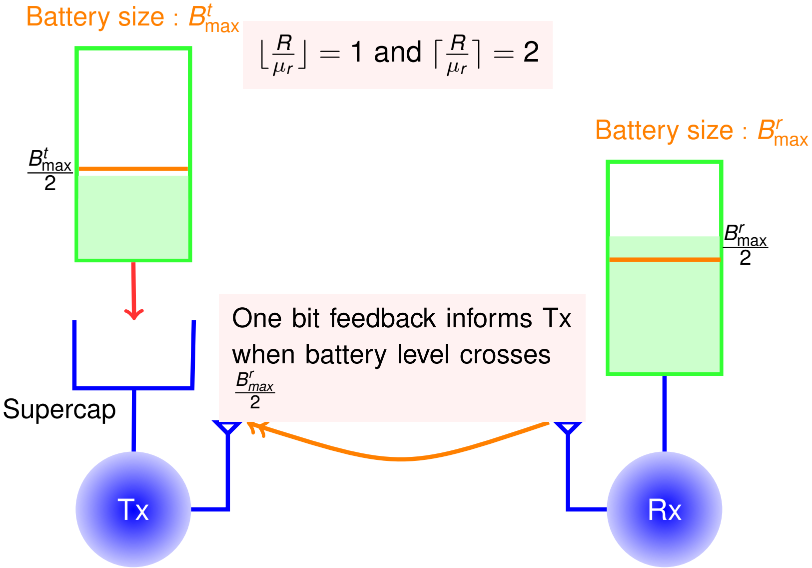

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Optimal Policy: Energy Constrained Receiver

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Policy at receiver

- Send 1-bit feedback whenever the battery level crosses the half-full mark

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Policy at receiver

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- Turns on after $N_{\text{on}} = \begin{cases} N_r & \text{if} \quad B_n^r \geq \frac{B_{\max}^r}{2} \\ N_r + 1 & \text{if} \quad B_n^r < \frac{B_{\max}^r}{2} \end{cases}$ slots where,

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Policy at transmitter

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Policy at transmitter

- Transmit only in the slots when receiver is on

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Policy at transmitter

- Transmit only in the slots when receiver is on
- Otherwise accumulate the energy in super-capacitor

Performance: 1-bit Feedback Policy

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- In addition,

$$\underbrace{\left(\frac{\mu_r}{R}\right)\log\left(1+\frac{R\mu_t}{\mu_r}\right)}_{\text{upper bound}} - \mathcal{T}^c - 1 = O\left(\frac{\log B^t_{\max}}{B^t_{\max}}\right).$$

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where $\mathcal{T}^c$: throughput achieved by 1-bit feedback policy

- Specifically,

$$\left(\frac{\mu_r}{R}\right)\log\left(1+\frac{R\mu_t}{\mu_r}\right) - \mathcal{T}^c = O\left(\frac{\log B^t_{\max}}{B^t_{\max}}\right) + O\left(\delta_r^+\right) + O\left(\delta_r^-\right).$$

where $\delta_r^+ = \frac{R}{\mu_r} - \lfloor \frac{R}{\mu_r} \rfloor$ and $\delta_r^- = \lceil \frac{R}{\mu_r} \rceil - \frac{R}{\mu_r}$

Time-dilation to Achieve Upper Bound

Policy at transmitter:

- Same as for 1-bit feedback policy

Policy at receiver:

- Receiver turn ON in last $f(.)$ slots of
  - $\lfloor \frac{Rf(.)}{\mu_r} \rfloor$ slots if battery is more than half full
  - $\lceil \frac{Rf(.)}{\mu_r} \rceil$ slots if battery is less than half full
- Effective drift goes to zero as $f(.)$ scales

Performance: Policy for Constrained Receiver

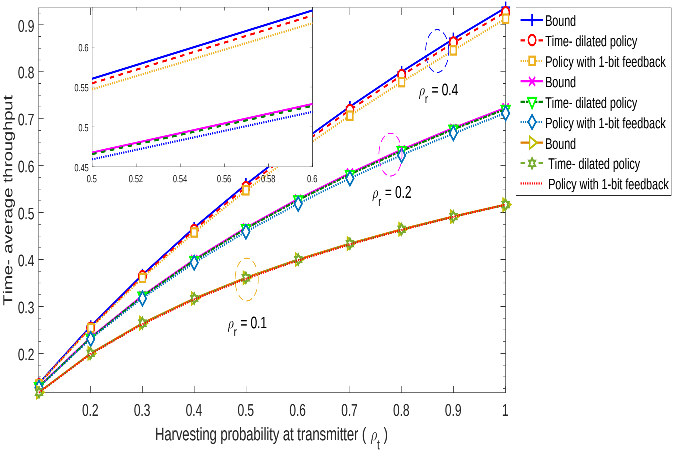

Figure: The result corresponds to time-dilation $f(\cdot) = 100$. Other parameters are $R = 0.5$ and $B^t_{\max} = B^r_{\max} = 1000$.

Fully Uncoordinated Policy

- Aim: to prescribe a deterministic pattern for the receiver
- Match the ratio of $N_r \triangleq \lfloor \frac{R}{\mu_r} \rfloor$ and $N_r + 1$ transmissions of 1-bit feedback policy

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Deterministic Policy $\mathcal{P}^{\text{uc}}$

- Compute $\frac{n^+}{n^-} = \frac{\sum_{n=1}^{N} \mathbb{1}_{\{B_n^t \geq B_{\text{max}}^r\}}}{\sum_{n=1}^{N} \mathbb{1}_{\{B_n^t < B_{\text{max}}^r\}}}$, for 1-bit feedback policy

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- Receiver turns on at the last slot of
  - Every batch of N_r slots for n^+ consecutive batches

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- Receiver turns on at the last slot of
  - Every batch of N_r slots for n^+ consecutive batches
  - Every $N_r + 1$ slots for n^- consecutive batches and so no
- Transmitter also follows this deterministic pattern

Fully Uncoordinated Policy

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  - Every batch of N_r slots for n^+ consecutive batches
  - Every $N_r + 1$ slots for n^- consecutive batches and so no
- Transmitter also follows this deterministic pattern
- $\mathcal{T}^c - \mathcal{T}^{uc} = O(\pi_0^{uc})$, where π_0^{uc} denotes the stationary probability that battery at either node is empty, under policy $\mathcal{P}^{uc}$

Fully Uncoordinated Policy

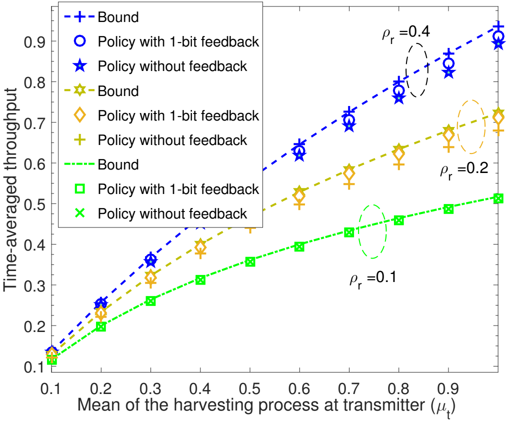


Figure: For $\mathcal{P}^{uc}$, the values of (n^+, n^-) are $(5, 1)$, $(1, 1)$ and $(2, 1)$ for $\rho_r = 0.1, 0.2$ and 0.4, respectively. Other parameters: $B^t_{\max} = B^r_{\max} = 50$, $R = 0.5$.

Numerical Results: Impact of battery size

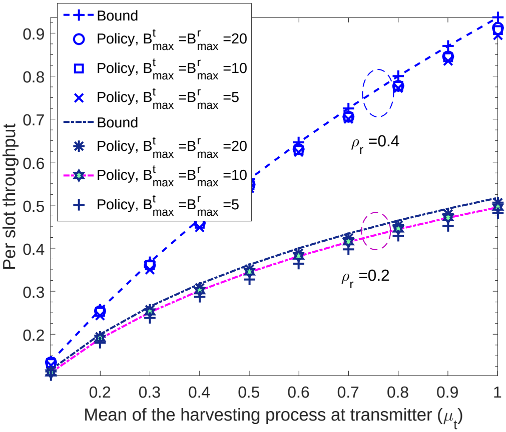


Figure: Impact of battery size on the throughput of policy $\mathcal{P}^c$, for $R = 0.5$.

Summary

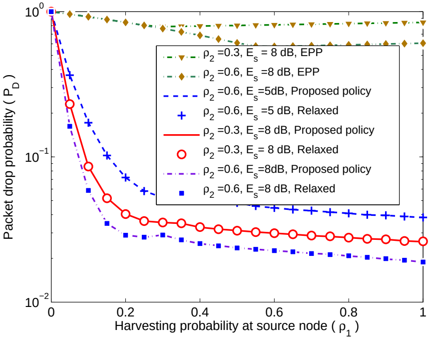
- Derived an upper-bound on the throughput of uncoordinated dual EH links
- Designed fully uncoordinated power control policies which achieve the upper-bound for unconstrained receiver
- Asymptotically optimal policies were proposed which require occasional 1-bit feedback
- Proposed a fully uncoordinated policy for a constrained receiver

Other Contributions of the Thesis

- Proposed a general framework to analyze the PDP of retransmission-based dual EH links
- Optimal policies for dual EH links with ARQ as well as HARQ-CC
- Optimal policies for spatio-temporally correlated EH processes

Thank You!

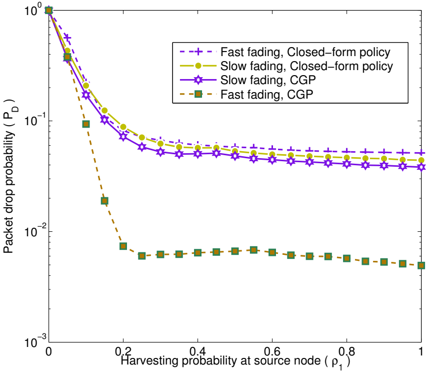
Performance of the Proposed Policy



No. of hops = 2
$R = 1$
$E_{max} = 10E_s$
$K_1 = K_2 = 4$

The policy obtained using proposed approach outperforms the equal power policy $[P_{max}\ P_{max}\ P_{max}\ P_{max}]$.

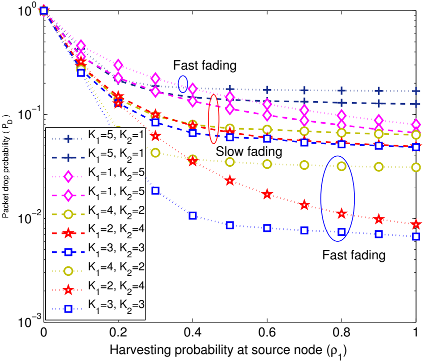
Performance of the Closed-form Policy for General Case



No. of hops = 2
$R = 1$
$E_{\max} = 10E_s$
$K_1 = K_2 = 4$

Performance of optimal policy designed by ignoring the energy cost of packet reception, compared to the near-optimal policy for the general case.

Impact of Slot Allocation Pattern



No. of hops = 2

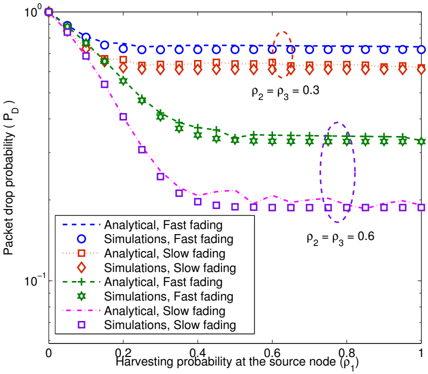
$R = 1$

$E_{max} = 10E_s$

$K_1 = K_2 = 4$

Impact of slot allocation on the PDP: equal slot allocation performs the best.

Accuracy of PDP Expressions



Accuracy of the closed-form PDP expressions. Parameters used: $K_1 = K_2 = 2$, $R = 1$, and $B^{\max} = 3$ for all the nodes. The RIP is $[1\ \ 1]$ at both source and relay nodes.