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1. Energy Harvesting Communication Using Finite-Capacity Batteries With Internal Resistance

Authors: Rajshekhar Vishweshwar Bhat, Mehul Motani, and Teng Joon Lim

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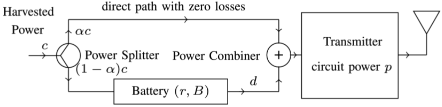

Figure: Dual path communication

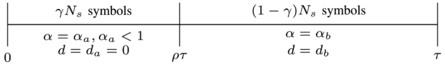

Figure: Frame structure

- Maximum achievable rate for TX over an AWGN channel with gain h, symbol energy P, and unit received noise PSD is $\mathbf{R} = \mathbf{log}(\mathbf{1} + \mathbf{hP})$ bits per channel symbol.

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- **Offline policy** (single frame)

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- **Offline policy** (Group of frames)

$$R_{\mathrm{avg}}(\boldsymbol{\rho}, \boldsymbol{\alpha}_a, \boldsymbol{\alpha}_b, \boldsymbol{\gamma}, \mathbf{d}_b) = \frac{1}{N} \sum_{i=1}^{N} R(\rho_i, \alpha_{a_i}, \alpha_{b_i}, \gamma_i, d_{b_i})$$

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- **Optimal Online Policy:** Stochastic dynamic programming, where state in frame n is $s_n = (C_n, H_n, B_{n-1})$

$$\mathcal{R}^*_{\text{on}} = \max_{\pi \in \Pi} \frac{1}{N} \sum_{n=1}^{N} \mathbb{E}\left[R(C_n, H_n, B_{n-1}, \rho_n, \alpha_{a_n}, \alpha_{b_n}, d_{b_n}) | s_1, \pi\right]$$

Offline single frame rate optimization problem:

$$
\begin{aligned}
\text{P0}: \underset{\rho,\alpha_a,\alpha_b,\gamma,d_b}{\text{maximize}} \quad & R(\rho, \alpha_a, \alpha_b, \gamma, d_b) && \text{(1a)}\\
\text{subject to} \quad & (\tilde{d}_b - \tilde{c}_b)(1-\rho)\tau - B_{\rho\tau} - B_0 \leq 0 && \text{(1b)}\\
& B_0 + B_{\rho\tau} - (\tilde{d}_b - \tilde{c}_b)(1-\rho)\tau - B \leq 0 && \text{(1c)}\\
& 0 \leq \rho \leq 1 && \text{(1d)}\\
& \alpha_c \leq \alpha_a, \alpha_b \leq 1 && \text{(1e)}\\
& 0 \leq d_b \leq D_p && \text{(1f)}\\
& (1-\alpha_b)d_b = 0 && \text{(1g)}
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Objective: Optimize time and power splitting ratios

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Objective: Optimize time and power splitting ratios

- Through an offline policy, assuming non-causal knowledge of harvested power and fading channel gains.
- Through sub-optimal policies when only statistics of energy arrivals and channel gains are known.

Contributions:

- Formulate a single frame optimization problem and derive compact expressions for optimal time and power sharing ratios, while incorporating the effects of battery internal resistance.

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- Solve for the optimal online policy by using stochastic dynamic programming. Also, propose three sub-optimal on-line algorithms which are practically feasible.

Contributions:

- Formulate a single frame optimization problem and derive compact expressions for optimal time and power sharing ratios, while incorporating the effects of battery internal resistance.
- Formulate an offline (non convex) optimization problem and propose an iterative algorithm to solve it.
- Solve for the optimal online policy by using stochastic dynamic programming. Also, propose three sub-optimal on-line algorithms which are practically feasible.
- Show via numerical simulations that the optimal policy designed for an ideal battery performs poorly when the internal resistance is not negligible

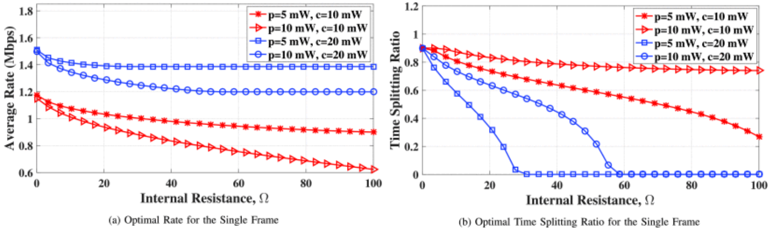
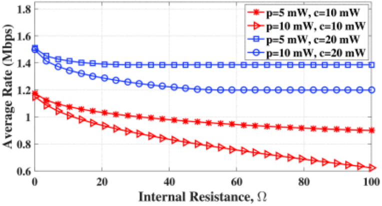
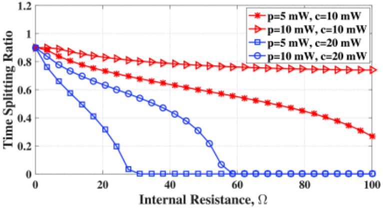


Figure: Optimal rate and time splitting ratios

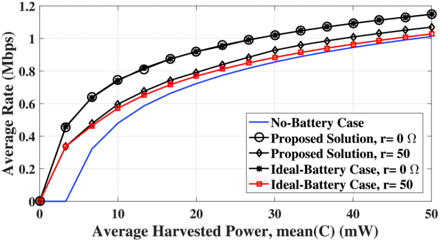


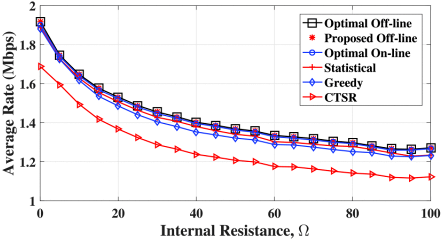
(a) Optimal Rate for the Single Frame



(b) Optimal Time Splitting Ratio for the Single Frame

Figure: Optimal rate and time splitting ratios





2. Online Ski Rental for ON/OFF Scheduling of Energy Harvesting Base Stations

Authors: Gilsoo Lee, Walid Saad, Mehdi Bennis, and Fumiyuki Adachi

- **Goal:** Minimize the operational costs (transmission delay and energy consumption) of a celluar network, in the presence of complete uncertainty of the energy harvesting process at the SBSs.

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- **Motivation:** Co-existence of SBSs with MBS boosts the capacity and coverage, but densifying the cellular network significantly increases energy consumption. Due to the uncertainty of energy arrival and the finite capacity of energy storage systems, self-powered SBSs must smartly optimize their ON and OFF schedule.

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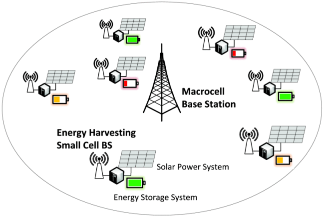

Approach:

- The operational cost of the BSs are computed in terms of transmission delay and energy consumption
- The original problem is decomposed into a set of distributed online optimization problems that are run at each SBS.
- The resulting problem is solved by a novel approach based on the ski rental problem. DOA (benchmark) and ROA (practical) are the two schemes used.

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Assumptions:

- SBSs and the MBS will use different frequency bands.
- Each UE can be connected with only one of the BSs at a certain time t within a period of T.
- Energy harvesting is assumed to be done irrespective of whether an SBS is turned ON or OFF.

System model

- State of BS

$$\sigma_j(t) = \begin{cases} 1, & \text{if SBS } j \text{ is turned ON at time } t, \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

System model

- State of BS

$$\sigma_j(t) = \begin{cases} 1, & \text{if SBS } j \text{ is turned ON at time } t, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

- Network Performance between UE i and SBS j

$$\gamma_{ij}(\boldsymbol{\sigma}(t)) = \frac{P_j^{\mathrm{tx}} \sigma_j(t) h_{ij}}{\sum_{j' \in \mathcal{B}^{\mathrm{on}} \setminus \{j\}} P_{j'}^{\mathrm{tx}} \sigma_{j'}(t) h_{ij'} + \rho^2} \quad (2)$$

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- Achievable data rate of UE i

$$c_{ij}(\boldsymbol{\sigma}(t)) = \frac{B}{|\mathcal{I}_j(t)|} \log_2(1 + \gamma_{ij}(\boldsymbol{\sigma}(t))) \quad (3)$$

System model

- **Transmission Delay:**

  For TX K bits b/w BS j, UE in $\mathcal{I}_j(t)$ at time t:

$$\phi_j(\boldsymbol{\sigma}(t)) = \sum_{i \in \mathcal{I}_j(\boldsymbol{\sigma}(t))} \frac{K}{c_{ij}(\boldsymbol{\sigma}(t))}. \tag{4}$$

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- **Power Consumption:**

$$\psi_j(\boldsymbol{\sigma}(t)) = \frac{|\mathcal{I}_j(\boldsymbol{\sigma}(t))|}{M}(1-q)P_j^{\mathrm{op}} + qP_j^{\mathrm{op}} \tag{5}$$

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- **Operational Expenditure of SBS:**

$$r_j(\boldsymbol{\sigma}(t)) = \alpha_D \phi_j(\boldsymbol{\sigma}(t)) + \alpha_P \psi_j(\boldsymbol{\sigma}(t)), \tag{6}$$

System model

- The Operational Expenditure of MBS (worst case) can be divided into per-SBS costs

$$\Phi_0^{\mathcal{I}_j(0)} = \sum_{i \in \mathcal{I}_j(0)} \frac{K}{\frac{B_m}{I} \log_2(1 + \gamma_{i0}(0))}. \quad (7)$$

$$\Psi_0^{\mathcal{I}_j(\boldsymbol{\sigma}(0))} = \frac{|\mathcal{I}_j(\boldsymbol{\sigma}(0))|}{M}(1-q)P_0^{\mathrm{op}} + qP_0^{\mathrm{op}}. \quad (8)$$

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- **Operational SBS Penatly / MBS expenditure:**

$$b_j = \alpha_B \left(\alpha_D \Phi_0^{\mathcal{I}_j(\boldsymbol{\sigma}(0))} + \alpha_P \Psi_0^{\mathcal{I}_j(\boldsymbol{\sigma}(0))} \right) T \tag{9}$$

System model

- ON/OFF Scheduling as an Online Optimization Problem

$$\min_{\boldsymbol{\sigma}(t),\boldsymbol{x}} \sum_{j=1}^{J} \left(\int_0^{u_j} r_j(\boldsymbol{\sigma}(\tau))\sigma_j(\tau)d\tau + b_j x_j \right), \tag{10}$$

$$\begin{aligned} \text{s.t. } & \sigma_j(t) + x_j \geq 1, \quad 0 \leq t \leq u_j, \ \forall j, \\ & \sigma_j(t) \in \{0,1\}, \quad 0 \leq t \leq u_j, \ \forall j, \\ & x_j \in \{0,1\}, \quad \forall j \end{aligned}$$

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- Proposition - (10) can be decomposed into j subproblems

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- **Competitive ratio** of an online algorithm is defined by

$$\kappa = \max_{u_j} \frac{\beta_{\mathrm{ALG}}(u_j)}{\beta_{\mathrm{OPT}}(u_j)}, \quad \forall u_j, \tag{12}$$

- **Online ski rental:**

$$\beta_{\mathrm{OPT}}(u_j) = \begin{cases} r_j u_j, & 0 \leq u_j \leq \dfrac{b_j}{r_j}, \\ b_j, & \dfrac{b_j}{r_j} \leq u_j \leq T. \end{cases} \tag{13}$$

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- **DOA:** SBS j is turned OFF at a predetermined time t_j , $0 tj T$

$$\frac{\beta_{\mathrm{DOA}}(u_j)}{\beta_{\mathrm{OPT}}(u_j)} = \begin{cases} \dfrac{r_j u_j}{\min\{r_j u_j, b_j\}}, & 0 \le u_j \le t_j, \\ \dfrac{r_j t_j + b_j}{\min\{r_j u_j, b_j\}}, & t_j \le u_j \le T, \end{cases} \tag{14}$$

when $u_j = t_j = \frac{b_j}{r_j}$, κ is minimized to 2.

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- **ROA:** κ is minimized to $\frac{e}{e-1} = 1.86$

Contributions:

- Novel approach to optimize the ON/OFF schedule of self-powered SBSs, formulating the problem as one of minimizing network operational costs during a period.
- Proposed DOA, ROA is shown to achieve the optimal competitive ratio for the approximated problem. Using the proposed ROA, each SBS can autonomously decide on its ON time without prior information on future energy arrivals.
- Simulation results show that both delay and ON/OFF switching overhead are significantly reduced when one adopts the online ski rental approach.

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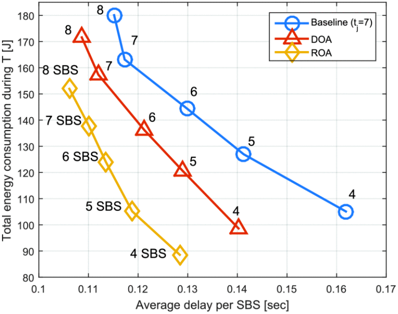
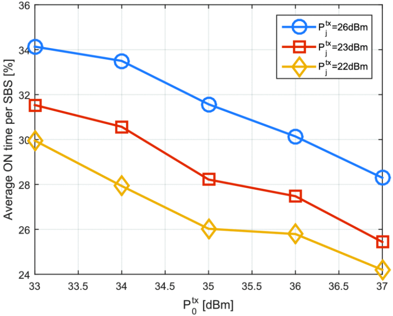
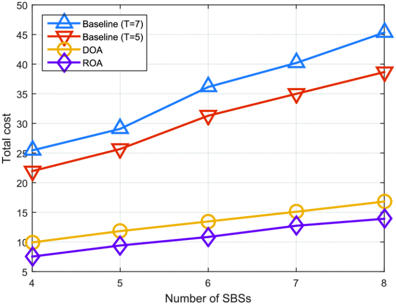
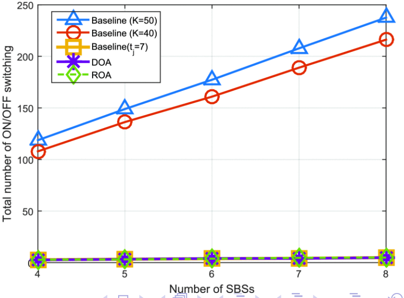
- Simulation results show that both delay and ON/OFF switching overhead are significantly reduced when one adopts the online ski rental approach.

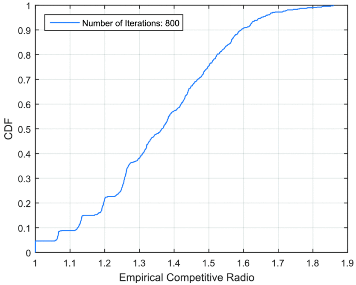
Numerical result: Compared with a baseline approach, ROA can yield performance gains reaching up to 15.6% in terms of reduced total energy consumption, up to 20.6% in terms of per-SBS network delay reduction, and can reduce up to 69.9% the total cost.

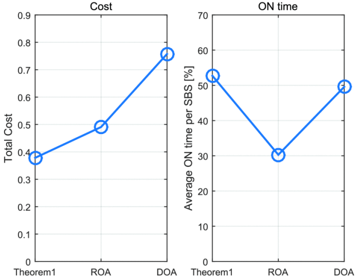

Total energy consumption during T [J]
Average delay per SBS [sec]
Baseline (t_j=7)
DOA
ROA
8 SBS
7 SBS
6 SBS
5 SBS
4 SBS


Average ON time per SBS [%]
P_0^tx [dBm]
P_j^tx=26dBm
P_j^tx=23dBm
P_j^tx=22dBm


Total cost
Number of SBSs
Baseline (T=7)
Baseline (T=5)
DOA
ROA


Total number of ON/OFF switching
Number of SBSs
Baseline (K=50)
Baseline (K=40)
Baseline(t_j=7)
DOA
ROA

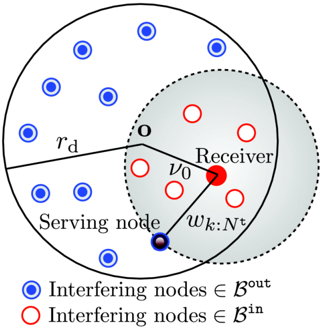

Number of Iterations: 800
CDF
Empirical Competitive Radio
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9


Cost
Total Cost
Theorem1
ROA
DOA
ON time
Average ON time per SBS [%]
Theorem1
ROA
DOA

3. Fundamentals of Modeling Finite Wireless Networks Using Binomial Point Process

Authors: Mehrnaz Afshang, and Harpreet S. Dhillon

Goal: Establish a generic mathematical framework to characterize the performance of an arbitrarily located reference receiver in a finite wireless network (based on two TX-selection policies).



- **TX selection policy**
  - Uniform - ad hoc networks
  - *k*-closest - Cellular networks
- **Locations of serving nodes** - Uniform BPP in a finite ball of radius r_d
- Assume noise negligible compared to interference

System Model

- **PDF of TX locations**

$$f(\mathbf{y}_i) = \begin{cases} \dfrac{1}{\pi r_{\mathrm{d}}^2} & \|\mathbf{y}_i\| \le r_{\mathrm{d}} \\ 0 & \text{otherwise.} \end{cases}$$

System Model

- **PDF of TX locations**

$$f(\mathbf{y}_i) = \begin{cases} \dfrac{1}{\pi r_{\mathrm{d}}^2} & \|\mathbf{y}_i\| \leq r_{\mathrm{d}} \\ 0 & \text{otherwise.} \end{cases}$$

- **TX-Selection Policies and Propagation Model**

$$\mathtt{SIR} = \frac{h_\ell \|\mathbf{x_0} - \mathbf{y}_\ell\|^{-\alpha}}{\sum_{\mathbf{y_i} \in \mathbf{\Phi}_{\mathrm{a}} \setminus \mathbf{y}_\ell} h_i \|\mathbf{x}_0 - \mathbf{y}_i\|^{-\alpha}},$$

System Model

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- **Coverage Probability**

$$\mathtt{P_c} = \mathbb{E}[\mathbf{1}\{\mathtt{SIR} \geq \beta\}] = \mathbb{P}(\mathtt{SIR} \geq \beta),$$

System Model

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- **Coverage Probability**

$$\mathrm{P_c} = \mathbb{E}[\mathbf{1}\{\mathtt{SIR} \ge \beta\}] = \mathbb{P}(\mathtt{SIR} \ge \beta),$$

- **Sequence of distances from TX to RX**

$$\text{PDF}: \ f_{W_i}(w_i) = \frac{2w_i}{r_{\mathrm{d}}^2}; \quad 0 \le w_i \le r_{\mathrm{d}}$$

- **Conditional PDF of the sequence**

$$f_{W_i}(w_i|\nu_0) = \begin{cases} f_{W_{i,1}}(w_i|\nu_0), & 0 \le w_i \le r_\mathrm{d} - \nu_0 \\ f_{W_{i,2}}(w_i|\nu_0), & r_\mathrm{d} - \nu_0 < w_i \le r_\mathrm{d} + \nu_0, \end{cases}$$

where $f_{W_{i,1}}(w_i|\nu_0) = \frac{2w_i}{r_d{}^2}$ and $f_{W_{i,2}}(w_i|\nu_0) = \frac{2w_i}{\pi r_d{}^2} \arccos(\frac{w_i{}^2 + v_0{}^2 - r_d{}^2}{2v_0 w_i})$

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- **Coverage Prob - Uniform TX-Selection Policy**

$$\begin{aligned} \mathrm{P}^{(u)}_{\mathrm{ref}}(\nu_0) = & \int_0^{r_\mathrm{d}-\nu_0} \mathcal{L}^{(u)}_{\mathcal{I}}(\beta r^\alpha|\nu_0) f_{W_{i,1}}(r|\nu_0)\mathrm{d}r \\ & + \int_{r_\mathrm{d}-\nu_0}^{r_\mathrm{d}+\nu_0} \mathcal{L}^{(u)}_{\mathcal{I}}(\beta r^\alpha|\nu_0) f_{W_{i,2}}(r|\nu_0)\mathrm{d}r, \end{aligned}$$

- **Conditional PDF of the sequence**

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- **Coverage Prob - Uniform TX-Selection Policy**

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- **Coverage Prob - k-closest TX-Selection Policy**

$$\mathrm{P}^{(k)}_{\mathrm{ref}}(\nu_0) = \int_0^{\mathrm{r_d}-\nu_0} \mathcal{A}(\beta r^\alpha, r, \nu_0) f^{(k)}_{R,1}(r|\nu_0)\mathrm{d}r + \int_{\mathrm{r_d}-\nu_0}^{\mathrm{r_d}+\nu_0} \mathcal{B}(\beta r^\alpha, r, \nu_0) f^{(k)}_{R,2}(r|\nu_0)\mathrm{d}r,$$

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  - Optimal # links that can be simultaneously activated to maximize NSE
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Extensions of work:

- Modeling - analyze Matern cluster process.
- Systems - performance analysis of indoor communication and hotspots.
- Study performance of mmWave communication systems with receiver experiencing blocking interference.

Other Interesting Papers

- Low-Rank Spatial Channel Estimation for Millimeter Wave Cellular Systems.
  Parisa A. Eliasi, Sundeep Rangan, and Theodore S. Rappaport
- MIMO Energy Harvesting in Full-Duplex Multi-User Networks.
  Ho Huu Minh Tam, Hoang Duong Tuan, Ali Arshad Nasir, Trung Q. Duong, and H. Vincent Poor
- Proactive Eavesdropping via Cognitive Jamming in Fading Channels.
  Jie Xu, Lingjie Duan, and Rui Zhang
- Joint Precoding and RRH Selection for User-Centric Green MIMO C-RAN.
  Cunhua Pan, Huiling Zhu, Nathan J. Gomes, and Jiangzhou Wang
- Load Optimization With User Association in Cooperative and Load-Coupled LTE Networks.
  Lei You and Di Yuan