An Energy-Renewal Approach With Wireless Power Transfer

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Outline

- Introduction
- Problem description
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Employing a mobile vehicle carrying a power-charging station to periodically visit each sensor node and charge it wirelessly.

**Device**

This *mobile wireless charging vehicle* (WCV) can either be manned by a human or be entirely autonomous.

**Wireless Power Transfer**
Renewable energy cycle

- Remaining energy level in a sensor node’s battery exhibits some periodicity over a time cycle.
- Formulate an optimization problem for joint flow routing and charging schedule for each sensor node.
  (Objective of maximizing the ratio of the WCV’s vacation time)
Introduction

Initial transient cycle

First cycle

Second cycle

$E_{\text{max}}$

$E_i$

$G_i$

$E_{\text{min}}$

$e_i$

$t$

$\tau$

$a_i$

$a_i + \tau_i$

$2\tau$

$a_i + \tau$

$a_j + \tau + \tau_i$

$3\tau$

Base Station

(a)

(b)
Parameter 1/2

- sensor nodes $N$
- battery capacity of $E_{\text{max}}, E_{\text{min}}$
- sensor node $i$ generates sensing data with a rate of $R_i$ (in bits/second)
- $f_{ij}$ the flow rate from sensor node $i$ to sensor node $j$ (b/s)
- $f_{iB}$ the flow rate from sensor node $i$ to the base station $B$ (b/s)
Flow balance constraint at each sensor node:

\[
\sum_{k \neq i} f_{ki} + R_i = \sum_{j \neq i} f_{ij} + f_{iB} \quad (i \in \mathcal{N}).
\]  

Energy consumption model:

\[
p_i = \rho \sum_{k \neq i} f_{ki} + \sum_{j \neq i} C_{ij} f_{ij} + C_{iB} f_{iB} \quad (i \in \mathcal{N})
\]  

- \(\rho\) is the rate of energy consumption for receiving a unit of data rate.
- \(C_{ij}\) (or \(C_{iB}\)) is the rate of energy consumption for transmitting a unit of data rate from node \(i\) to node \(j\) (or the base station \(B\)).
Parameter 2/2

- \( V \) is traveling speed of the WCV (m/s)
- \( U \) the energy transfer rate of the WCV
- Charge the sensor node \( i \), spend a time of \( \tau \)
- After the WCV visits all the sensor nodes, it will return to its service station, call this resting period vacation time, denoted as \( \tau_{vac} \)
Problem description

- $P = (\pi_0, \pi_1, \ldots \pi_N, \pi_0)$ the path traversed by the WCV

- The cycle time $\tau$ can be written as

$$\tau = \tau_p + \tau_{\text{vac}} + \sum_{i \in N} \tau_i$$

- Denote $D_p$ the distance of path $P$, $\tau_p = D_p / V$
Optimal traveling path

\textbf{OPT-R}

\begin{align*}
\text{max } \eta_{\text{vac}} \\
\text{s.t. } & \sum_{j \neq i} f_{ij} + f_{iB} - \sum_{k \neq i} f_{ki} = R_i (i \in \mathcal{N}), \\
& \eta_{\text{vac}} \leq 1 - \sum_{k \in \mathcal{N}} \eta_k - \frac{U \cdot \tau_{\text{TPS}}}{E_{\text{max}} - E_{\text{min}}} \cdot \eta_i \cdot (1 - \eta_i) \quad (i \in \mathcal{N}), \\
& f_{ij}, f_{iB} \geq 0, 0 \leq \eta_i, \eta_{\text{vac}} \leq 1 \quad (i, j \in \mathcal{N}, i \neq j).
\end{align*}

Flow conservation constraint

Energy constraint
Construction of a Near-Optimal Solution

1. Given a target performance gap $\epsilon$.
2. Let $m = \left\lceil \sqrt{\frac{U \tau_{TSP}}{4\epsilon(E_{\text{max}} - E_{\text{min}})}} \right\rceil$.
3. Solve Problem OPT-L with $m$ segments by CPLEX, and obtain its solution $\hat{\psi} = (\hat{f}_{ij}, \hat{f}_{iB}, \hat{\eta}_i, \hat{\lambda}_{ik}, \hat{\zeta}_i)$.
4. Construct a feasible solution $\psi = (f_{ij}, f_{iB}, \eta_i, \eta_{\text{vac}})$ for Problem OPT-R by letting $f_{ij} = \hat{f}_{ij}$, $f_{iB} = \hat{f}_{iB}$, $\eta_i = \hat{\eta}_i$ and $\eta_{\text{vac}} = \min_{i \in N} \left\{ 1 - \sum_{k \in N} \hat{\eta}_k - \frac{U \tau_{TSP}}{E_{\text{max}} - E_{\text{min}}} \cdot \hat{\eta}_i \cdot (1 - \hat{\eta}_i) \right\}$.
5. Obtain a near-optimal solution $(f_{ij}, f_{iB}, \tau, \tau_i, \tau_{\text{vac}}, p_i)$ to Problem OPT by Algorithm 1.
Simulation Settings

- Consider a randomly generated WSN consisting of 50 nodes
- Sensor nodes over a square area of 1 km × 1 km
- The traveling speed of the WCV is $V = 5$ m/s
- Let $E_{max} = 10.8$ KJ, $E_{min} = 5.4$ KJ
- $U = 5W$
In this optimal cycle, 
\[ D_{TSP} = 5821 \text{ m} \] and 
\[ \tau_{TSP} = 1164.2 \text{ sec} \]

- target \( \epsilon = 0.01 \), \( m = 4 \)
- \( \tau = 17.34 \text{ hour} \)
- \( \tau_{ac} = 1164.2 \text{ sec} \)
- \( \eta_{vac} = 77.51\% \)
Numerical Results

Renewable cycle

- Initial transient cycle
- First renewable cycle
- Second renewable cycle

$E_{\text{max}} = 10800$

$E_{\text{i}} = 8628$

$E_{\text{min}} = 540$

$t(s)$