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P^3: Joint Optimization of Charger Placement and Power Allocation for Wireless Power Transfer

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Pervasive Mobile Devices

- In 2014
  - # of mobile devices > world's population
- By 2019
  - nearly 1.5 mobile devices per capita

Battery-powered

Cisco VNI, accessed by Apr. 2015

When Your Phone Runs Out of Battery

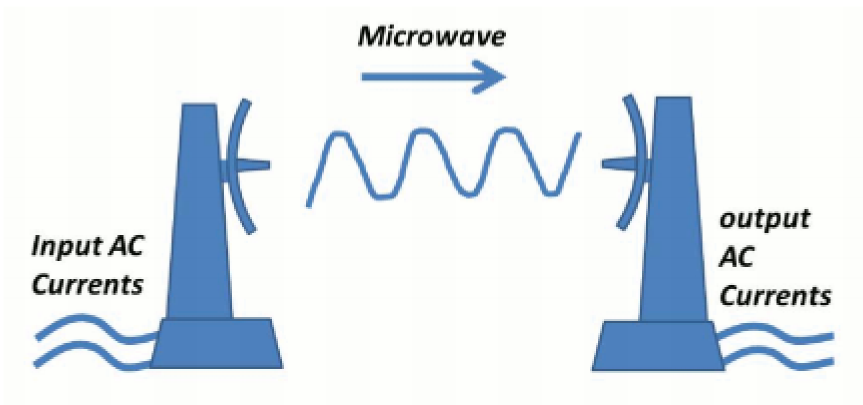
Current Solutions

- Energy conservation
  - Cannot compensate for energy depletion
- Energy harvesting
  - Unpredictable, unstable, uncontrollable
- …

Wireless power transfer

Wireless Power Transfer (WPT)

- Energy can be wirelessly transmitted from power chargers to energy receiving devices (RFID tags, sensors, smartphones, tablets, even Tesla cars).



Kurs et al., Wireless power transfer via strongly coupled magnetic resonances, Science.

Related Work on WPT

- Maximizing network lifetime [Peng et al., RTSS'10]
  - Selecting charging sequence
- Optimizing charging efficiency [Shi et al., INFOCOM'11]
  - Charging path plan to maximize the ratio of charger's vocation time over cycle time
- Energy provisioning [He et al., INFOCOM'11]
  - Placing RFID readers to cover a network
- Minimizing charging delay [Fu et al., INFOCOM'13]
  - Selecting charging stop locations and durations
- Collaboration between chargers [Zhang et al., TC'14]
  - Using multiple chargers' collaboration

Motivation

- Place a set of static chargers to provide wireless power charging service in an area of interest.
  - Campus, park, highway, etc.

The Problem In a Nut Shell

- Multiple stationary power receiving devices
- Multiple preselected candidate locations for placing chargers
- Adjustable power of a charger
- Constraint: the total power allocated to all chargers is limited.
- Objective: maximize the charging quality by intelligently selecting a subset of candidate locations and the respective power levels

Basic Notations

- A set of *M* stationary devices

$$S = \{s_1, s_2, \dots, s_i, \dots s_M\}$$

- A set of *N* preselected locations for placing chargers

$$C = \{c_1, c_2, \dots, c_N\}$$

  - Based on historical data analysis and market investigateion
  - A charger placement $C' \subseteq C$

- Euclidean distance between two entities

$$d(c_i, s_j)$$

Adjustable Power

- Each charger can be operated at *L* different power levels

$$p_i = p(h_i) = h_i \times p_{min}$$

  - p_i : the power of charger c_i
  - h_i : the power level of charger c_i
  - $\mathbf{H} = (h_1, h_2, \ldots, h_N)$: a power allocation

Charging Model

$$p(c_i, s_j) = \begin{cases} \dfrac{\alpha}{\left(d(c_i, s_j) + \beta\right)^2} p(h_i), & d(c_i, s_j) \le D(h_i) \\ 0, & \text{otherwise} \end{cases}$$

- c_i: charger
- s_j: power receiving device
- $p(h_i)$: power of the charger c_i
- $p(c_i, s_j)$: the power received by s_j from c_i
- $D(h_i)$: the maximum covering distance of power level h_i
- α and β: fixed parameters depending on environments and tranmistting hardware

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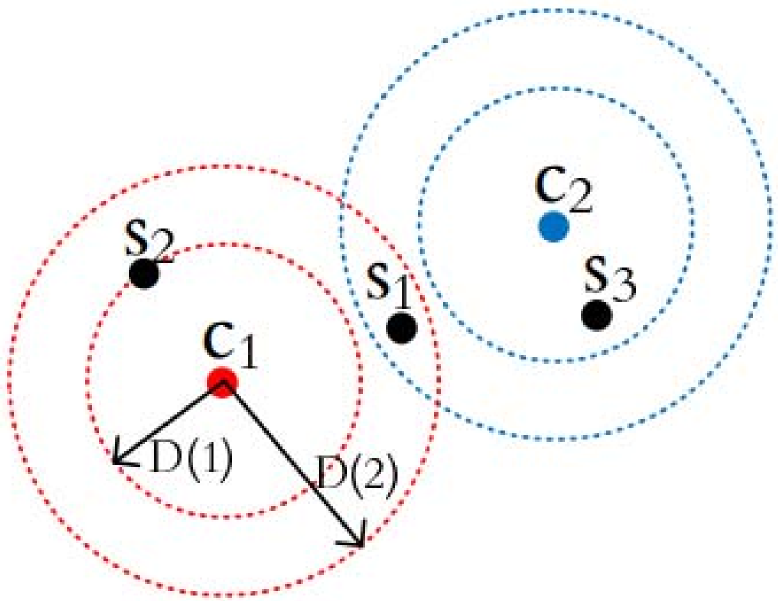
S. He, et al., Energy Provisioning in Wireless Rechargeable Sensor Networks, IEEE INFOCOM 2011.

Charging Model

- Power received from multiple chargers is additive.
  - Given a charger placement C' and a power allocation $\mathbf{H}$, the total power $p_{C'}(sj)$ received by s_j is

$$p_{C'}(s_j) = \sum_{c_i \in C'} p(c_i, s_j)$$



$C' = \{c_1, c_2\}$ and $\mathbf{H} = (1, 2)$

$$p_{C'}(s_1) = p(c_2, s_1)$$

$$p_{C'}(s_2) = p(c_1, s_2)$$

$$p_{C'}(s_3) = p(c_2, s_3)$$

Charging Quality

- P_j: the maximum power consumption rate of s_j
- The charging quality of a charger placement C' and a power allocation $\mathbf{H}$ on a device s_j is

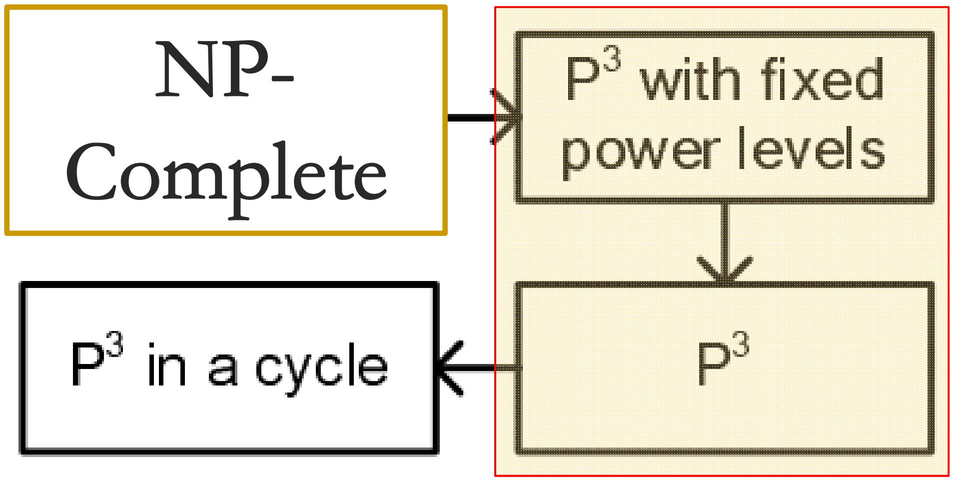
$$Q_{C'}(s_j) = \min\{p_{C'}(s_j), P_j\}$$

- The charging quality of a charger placement C' and a power allocation $\mathbf{H}$ on all devices is

$$Q(C', \mathbf{H}) = \sum_{j=1}^{M} Q_{C'}(s_j)$$

The P^3 Problem

Problem 1: (**Charger Placement and Power Allocation Problem, $\mathbf{P^3}$**) Given a set C of candidate locations, a set S of devices, and a power budget B, P^3 is to find a charger placement C' and a power allocation $\mathbf{H}$ to maximize $Q(C', \mathbf{H})$, subject to the power budget constraint, *i.e.*, $\sum_{c_i \in C'} p_i \leq B$.



P^3 with Fixed Power Levels

- The power level h_i is constant for all locations.
  - Uniform case: $h_1 = h_2 = \dots = h_N = h$
  - Non-uniform case

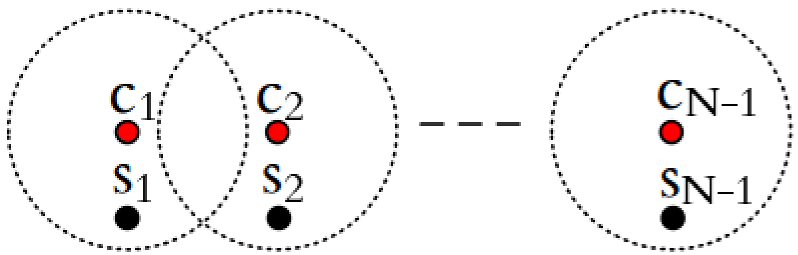
Fixed Power Levels: Unifrom Case

- $Q(C', \mathbf{H})$ degenerates into $Q(C')$.
- $Q(C')$ is nonnegative, monotone, and submodular.
  - Details can be found in the paper.
- (1-1/e)-approx. algorithm
  - Starting with an empty set, add the location that maximize the marginal gain of $Q(C')$:

$$c \leftarrow \arg\max_{c \in C \setminus C'} \left(Q(C' \cup \{c\}) - Q(C') \right)$$

Fixed Power Levels: Non-unifrom Case

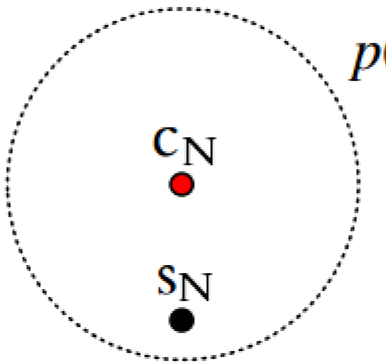
$$c \leftarrow \arg\max_{c \in C \setminus C'} \left(Q(C' \cup \{c\}) - Q(C') \right)$$



$$M = N = L + 1$$

$$h_1 = h_2 = \ldots = h_{N-1} = 1, \text{ and } h_N = L$$

$$p(c_1, s_1) = p(c_2, s_2) = \ldots = p(c_{N-1}, s_{N-1}) = p(c_N, s_N) - \epsilon$$



$$B = L \cdot p_{\min}$$

c_N	$c_1, \ldots, c_{N-1}$
$p(c_1, s_1) + \epsilon$	$L \cdot p(c_1, s_1)$

$$\sim \frac{1}{L}$$

Fixed Power Levels: Non-unifrom Case

$$c_x \leftarrow \arg \max_{c_x \in C \setminus C', \sum_{c_i \in C' \cup \{c_x\}} p_i \le B} \frac{Q(C' \cup \{c_x\}) - Q(C')}{p_x}$$

$$\sim \frac{1}{L}$$

Return the better one of these two results

$$\frac{1}{2}(1 - \frac{1}{e})$$

P^3

- With fixed power levels
  - Uniform case: 1-1/e
  - Non-uniform case: $\frac{1}{2}(1-\frac{1}{e})$
- How about P^3 in the general sense?

$$\frac{1-1/e}{2L}$$

P^3

- VP^3: for each candidate location c_i, we are given L different "virtual" chargers with constant but exactly different power levels, i.e., 1, 2, …, and L.
- Main idea
  - Find a solution to VP^3
    - Using the aforementioned basic algorithms
  - Tailor the obtained solution for P^3
    - Retaining only the charger with the maximum power level for each location
    - Utilizing the remaining budget
- Details can be found in the paper.

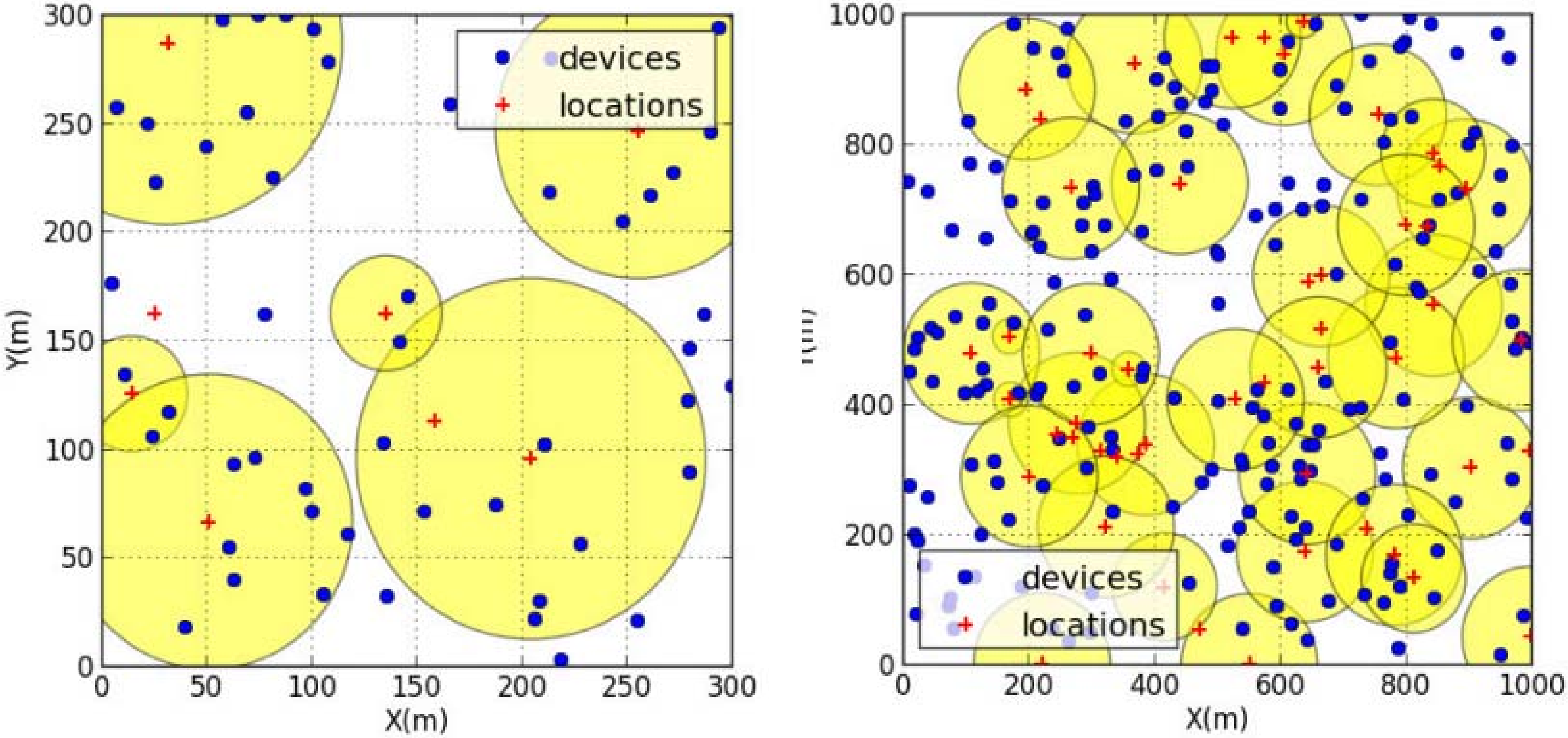
Baseline Setup

- Optimal algorithm (OPT)
- Fixex level algorithm (FLA)

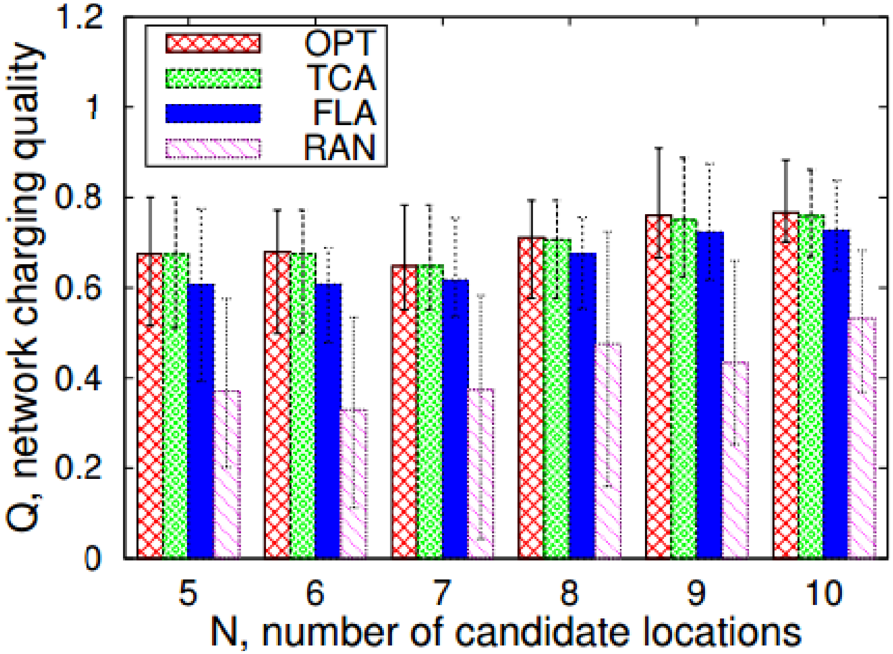
$$h_i = \arg \max_{h_i \in \{1,\ldots,L\}} \frac{\sum_{j=1}^{M} Q_{\{c_i\}}(s_j)}{p(h_i)}$$

- Random algorithm (RAN)

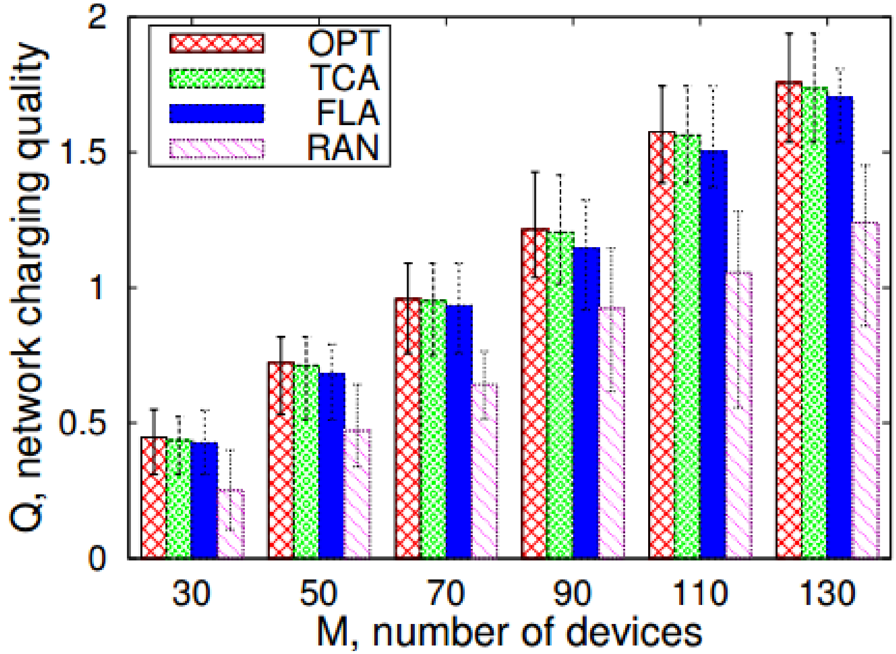
Placement Examples



Evaluation Results



(a) Varying the number of locations



(b) Varying the number of devices

The gap between our algorithm (TCA) and OPT is 4.5% at most and 2.0% on average.

Conclusion

- To the best of our knowledge, we are the first to study the joint optimization of charger placement and power allocation problem. We show the problem is NP-Complete.
- We propose two approx. algorithms for P^3 with and without fixed power levels, the effectiveness of which is evaluated through extensive simulations.
- Future work: implementation, battery network, etc.

Thank you for your attention!

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