Course "Algorithmic Foundations of Sensor Networks" Lecture 11: Wireless Power Transfer

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Wireless Power Transfer (WPT)

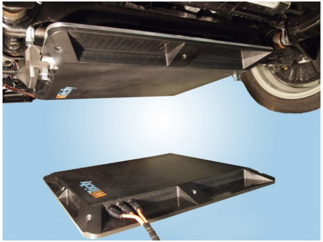
- A **WPT system** consists of:
  - **chargers** which transmit power **wirelessly**
  - **receivers** which **harvest** the energy from the chargers
- Envisioned by **Tesla**, now becoming a game-changing technology.[1]
- **More reliable and controllable** than ambient energy harvesting (solar, light, wind etc.)

[1] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher and M. Soljacic, Wireless power transfer via strongly coupled magnetic resonances, Science, vol. 317, pp. 83, 2007.

Two Basic Technologies

- **Radio frequency** (RF): low charging efficiency, only support low-power devices, charging distance up to few meters (0.13% efficiency).
- **Resonant magnetic coupling**: high charging efficiency, support high-power equipment (e.g. electrical vehicle), charging distance < 1 m ($91 - 93$% efficiency).

(a) Electromagnetic radiation products from Powercast Corp.



(b) Resonant magnetic coupling from WiTricity charges electrical vehicle.

A new, rapidly evolving domain

- WPT has recently evolved to:
  - a subject of rapid **technological** progress
  - a very active **research** topic
  - a domain of emerging **practical development** and commercial application
- **Specialized** journals, conferences and first books have appeared.
- **Wireless Power Consortium** - Cooperation of Asian, European, and American companies in diverse industries. Working towards the **global standardization** *charging technology* **(Qi standard)**.
- **Alliance for Wireless Power** - Independently operated organization composed of global wireless power and technology industry leaders **(Rezense standard)**.
- **Commercial products** utilizing wireless power transfer are already available in the market.

Commercial products

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Apple has joined the Wireless Charging Consortium, hinting at iPhone 8 feature CREDIT: CONCEPTSIPHONE

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Would YOU let a friend share your phone battery? Sony patents technology for wireless power transfer between devices

- **Sony has patented tech to let you 'steal' battery power from nearby devices**
- **Phones could search for power in a similar way to seeking out Wi-Fi hot spots**
- **A chip with data transfer technology could enable power exchange wirelessly**

By DAISY DUNNE FOR MAILONLINE
PUBLISHED: 12:47 BST, 17 March 2017 | **UPDATED:** 13:51 BST, 17 March 2017

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Wireless Power Market Surges Forward in 2017

April 20, 2017 | IHS Markit

Reading time 2 min (612 words)

IHS Markit today announced that the market for wireless power and charging is expected to grow in 2017, with global receiver shipments reaching 325 million units by year end. The market grew approximately 40% in 2016.

According to the new IHS Markit 2017 Wireless Power Tracker, mobile phones remain the primary driver for development of wireless power technology and mobile phones, laptops and wearable devices will drive receiver market growth. Receiver unit shipments are expected to climb this year as demand increases; OEMs make their decision on specifications; and the market moves towards glass-backed phones.

In 2016, the flagship Samsung handset made the biggest single contribution to enabled receiver shipments. Samsung's decision to retain wireless charging on the Galaxy S7, and LG's decision to add the technology to its new G6 device (U.S. model), were crucial for wireless charging technology. Apple is expected to follow suit later this year with its next iPhone, further boosting receiver shipments.

"The mobile phone market continues to be the entry point for the consumer experience of wireless power," said Vicky Yussuff, Analyst for IHS Markit. The IHS Markit Q1 consumer survey shows that consumer awareness of wireless power technology remains high and, perhaps more significantly, there has been a jump in usage. "More than one-third (35%) of U.S. consumers say they have used wireless charging, up from 25% in 2016. This suggests the market has moved into the commoditization phase, particularly for mobile phones." Yussuff said.

Market projection

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7 APRIL 2017 BY MACIEJ HEYMAN

Wireless Charging Market Products Will Net Revenues Worth US$ 27 Billion by 2024

New York, NY — (SBWIRE) — 04/07/2017 — As we head towards an era where wires won't necessarily be a requisite for powering up devices, tech companies from around the world are intensifying their efforts towards production of advanced and immaculate wireless charging systems. Innovative technologies supporting the working mechanism of wireless charging devices is also piquing the curiosity of tech enthusiasts as well as common consumers. From green vehicles to smartphones, Persistence Market Research has published its research study on how wireless charging is spanning the globe as the next-gen mode of charging electric devices.

A crucial need

- **A solid foundational and algorithmic framework** seems still necessary for WPT to achieve its full potential.
- In this respect, this talk presents:
  - different abstract **models** (scalar, vector, peer to peer)
  - interesting **concepts and phenomena** (super-additive, cancellation)
  - key **optimization problems** (power maximization, energy balance, radiation control)

Structure of the lecture

1. Radiation Aware Wireless Charging in the Scalar model
2. Power Maximization in the Vector Model
3. Peer to Peer Wireless Energy Exchange
4. Future Trends

S. Nikoletseas, T. Raptis, C. Raptopoulos, Low Radiation Efficient Wireless Energy Transfer in Wireless Distributed Systems, in ICDCS 2015.

Also in the Journal of Computer Networks (COMNET 2017).

On Electromagnetic Radiation

- Wireless Charger Stations create **strong electromagnetic fields**
- WPT introduces a new source of electromagnetic radiation (EMR) that co-exists with several other wireless technologies (i.e., Wi-Fi, Bluetooth, cellular etc.).
- Exposure to high electromagnetic radiation has been recognized as a critical issue with potential implications to human health.
- **Controversial** matter, so we focus on **how to control EMR** without however compromising the QoS experienced by users.

Novelty

- We define a novel charging model that takes into account **real hardware** restrictions:
    - finite initial charger energy supplies (it can transfer restricted energy)
    - finite node battery capacity (it can store restricted energy)

    => non-linear constraints (time multiplies power) that radically change the complexity of the computational problems we consider

    => we focus on **"useful energy"** received (not just power rate)

- We present and study the *Low Radiation Efficient Charging Problem (LREC)*.

    objective function: amount of useful energy transferred from chargers to nodes under constraints on the maximum level of radiation

The model (1/2)

- n rechargeable nodes $\mathcal{P} = \{v_1, v_2, \ldots, v_n\}$ and m wireless chargers $\mathcal{M} = \{u_1, u_2, \ldots, u_m\}$ deployed inside an area of interest $\mathcal{A}$.
- $E_u^{(t)}$ and r_u are the available energy at time t and charging radius of charger $u \in \mathcal{M}$.
- $C_v^{(t)}$ is the remaining energy storage capacity of node $v \in \mathcal{P}$, at time t.

Assumptions:

- [Charging] A node $v \in \mathcal{P}$ harvests energy from a charger $u \in \mathcal{M}$ with charging rate given by

$$P_{v,u}(t) = \begin{cases} \frac{\alpha r_u^2}{(\beta + \mathrm{dist}(v,u))^2}, & \text{if } E_u^{(t)}, C_v^{(t)} > 0,\ \mathrm{dist}(v,u) \leq r_u \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

α and β are known positive constants determined by the environment and hardware.

- [Energy] The harvested energy by the nodes is additive. Therefore, the total energy that node v gets within the time interval $[0, T]$ is

$$H_v(T) = \sum_{u \in \mathcal{M}} \int_0^T P_{v,u}(t)dt. \tag{2}$$

- [EMR] The *electromagnetic radiation (EMR)* at a point x is proportional to the additive power received at that point. In particular, for any $x \in \mathcal{A}$, the EMR at time t on x is given by

$$R_x(t) = \gamma \sum_{u \in \mathcal{M}} P_{x,u}(t), \tag{3}$$

where γ is a constant that depends on the environment.

- Let $\mathcal{M}$ a set of **chargers** and $\mathcal{P}$ be a set of **nodes** in an area $\mathcal{A}$. Suppose that

(i) each charger $u \in \mathcal{M}$ initially has available energy $E_u^{(0)}$

(ii) each node $v \in \mathcal{P}$ has initial energy storage capacity $C_v^{(0)}$

- [Objective] Assign to each charger $u \in \mathcal{M}$ a radius r_u, so that

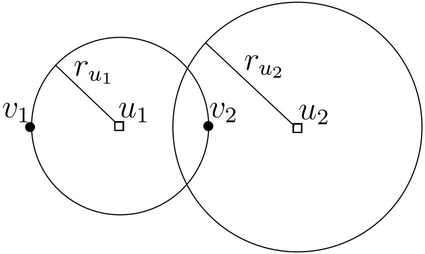
(a) the total usable energy given to the nodes of the network is maximized

(b) the electromagnetic radiation at any point of $\mathcal{A}$ is at most ρ.

- The objective function to be **maximized** is denoted by

$$f_{\text{LREC}}\left(\vec{r}, \vec{E}^{(0)}, \vec{C}^{(0)}\right) = \sum_{u \in M}(E_u^{(0)} - \lim_{t \to \infty} E_u^{(t)}) = \sum_{v \in P}(C_v^{(0)} - \lim_{t \to \infty} C_v^{(t)})$$

An informative example



A network with 2 chargers u_1, u_2 and 2 nodes v_1, v_2. All 4 points are collinear and $\text{dist}(v_1, u_1) = \text{dist}(v_2, u_1) = \text{dist}(v_2, u_2) = 1$. Also, we take $\rho = 2$ and $E_{u_1}^{(0)} = E_{u_2}^{(0)} = C_{v_1}^{(0)} = C_{v_2}^{(0)} = 1$

- The optimal solution of LREC is when $r_{u_1} = 1$ and $r_{u_2} = \sqrt{2}$.
- Observation: $f_{\text{LREC}}\left(\vec{r}, \vec{E}^{(0)}, \vec{C}^{(0)}\right)$ **is not necessarily increasing in** $\vec{r}$. (*Proof idea.* Increasing r_{u_1} in the above example reduces the objective function value.)

Computing the Objective Function: Main idea and Running time

- Main algorithmic idea: Given the configuration (i.e., radii, charger energies, node capacities) at t, we can find which charger (or node) will next deplete its energy (or reach its storage capacity) and when!
  - Consider for each charger all nodes it charges, and for each node all chargers it receives energy from. Find **the next one** depleted/saturated and the time.
  - In each round, we find **the minimum among those times** and we evaluate the energy exchanged.
  - We **repeat** until all chargers are depleted and all nodes are full.

- So, we get the following:

Lemma

$f_{LREC}\left(\vec{r}, \vec{E}^{(0)}, \vec{C}^{(0)}\right)$ can be computed in $O(n+m)$ rounds of $O(n+m)$ time each.

Proof idea. In every iteration, the algorithm sets to 0 the energy level or the capacity of at least one charger or node. □

Computing the Maximum Radiation

- Unfortunately, it is not obvious how to use the special formula for the EMR to find **where the radiation is maximized** and some kind of discretization is necessary.

- Therefore, we use the following generic random sampling procedure: for sufficiently large $K \in \mathbb{N}^+$, choose K points uniformly at random inside $\mathcal{A}$ and return the maximum radiation among those points.

- The computation of the EMR takes $O(m)$ time, since it depends only on the distance of that point from each charger in $\mathcal{M}$.

On the computational hardness of LREC

We consider the following relaxation: *Low Radiation Disjoint Charging (LRDC) problem*

- General setup is similar to LREC
- [Unique Charging] We impose the additional constraint that no node should be charged by more than 1 charger (to minimize unnecessary overlaps and reduce radiation).

Theorem

LRDC is NP-hard.

Proof idea: Reduction from the Independent Set Problem in Disc Contact Graphs. □

- This indicates a **high computational complexity** of LREC itself.
- Actually, we give an Integer Linear Program (ILP) formulation for LRDC.
  ILP is known to be NP-hard.

Three algorithms

- an **approximate** linear programming relaxation to *LRDC*.
- a "**charging-oriented**" solution, where each radius is set to maximum.
- a **local improvement heuristic for LREC**, which **progressively** finds the best radius for each charger assuming the radii of all the rest chargers are fixed.

A Local Improvement Heuristic for LREC

Main Idea of algorithm:

Choose a charger u at random. Assuming all rest m-1 radii fixed, we can approximately determine the radius r_u which achieves the best objective function value:

- For $i = 0, 1, \ldots, \ell$ (ℓ large enough), set $r_u = \frac{i}{\ell}\text{diam}(\mathcal{A})$ and compute for each such value

  (a) the objective function value and
  (b) the maximum EMR.

Iterate the above K' times by choosing at random a different charger each time.

Lemma

The above process terminates in $O\left(K'((n+m)^2 + mK)l\right)$ *steps.*

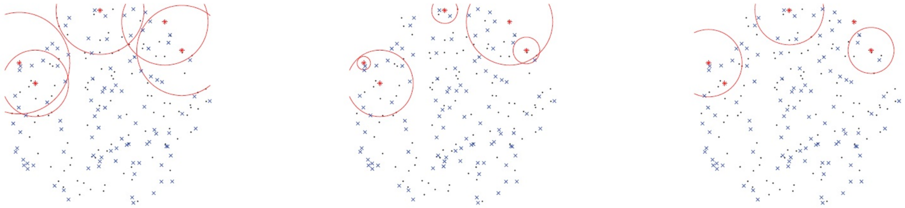
An approximate method

- We use the Linear Program (+rounding) from the relaxation of the IP as a **performance upper bound** to evaluate our algorithmic solutions
- The solution to the relaxed LRDC gives a low radiation solution to LREC.

Experimental settings

- Simulation environment: Matlab R2014b.
- We compare `IterativeLREC`, `IP-LRDC` (after the linear relaxation) and the "`ChargingOriented`" protocol
- We deploy uniformly at random, $|\mathcal{P}| = 100$ network nodes, $|\mathcal{M}| = 10$ wireless chargers and $K = 1000$ points of radiation computation.
- We set $\alpha = 0, \beta = 1, \gamma = 0.1$ and $\rho = 0.2$.
- Three basic metrics:
  - charging efficiency
  - maximum radiation
  - energy balance among the nodes

Network snapshot

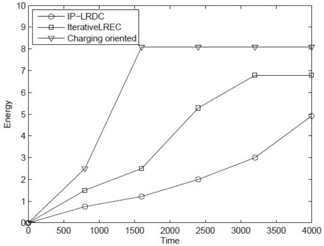


(a) ChargingOriented (b) IterativeLREC (c) IP-LRDC

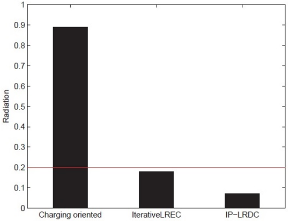
Network snapshot using 5 chargers.

- The radii of the chargers in the **ChargingOriented** case are larger than in the other two cases.
- In IP-LRDC the **radiation constraints** lead to a configuration where two chargers are not operational.
- IterativeLREC provides a configuration **"in between"** the ChargingOriented and IP-LRDC, in which some overlaps of smaller size are present.

Charging efficiency and Radiation



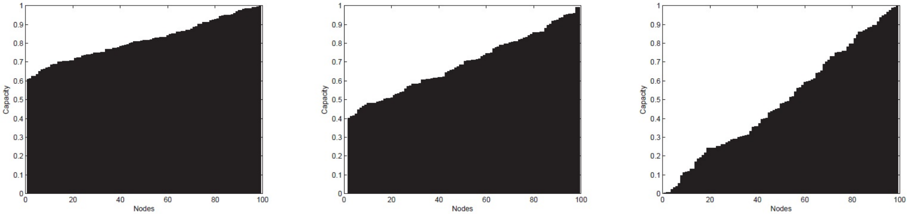
Charging efficiency over time.



Maximum radiation.

- The `ChargingOriented` method is the most efficient (w.r.t. energy) and fast but it results in high maximum radiation.
- `IP-LRDC` achieves the lowest charging efficiency of all due to the small charging radii and consequently small network coverage by the chargers.
- Our heuristic `IterativeLREC` achieves high enough efficiency w.r.t. the radiation constraints.

Energy balance



(a) `ChargingOriented` (b) `IterativeLREC` (c) `IP-LRDC`

Energy balance

- Graphical depiction of the **energy provided to the various nodes** throughout the experiment.
- `IterativeLREC` achieves efficient energy balance that approximates the performance of the powerful `ChargingOriented`

Summary

- New (finite) charging model and Low Radiation Efficient Charging Problem, in which we wish to optimize the amount of **"useful" energy** transferred from chargers to nodes (under constraints on the **maximum level of radiation**).
- We present several fundamental properties of this problem and provide indications of its hardness.
- Also, we propose an efficient iterative local improvement heuristic for LREC, which runs in polynomial time.

2. Power Maximization in the Vector Model

I. Katsidimas, S. Nikoletseas, T. Raptis and C. Raptopoulos. Efficient Algorithms for Power Maximization in the Vector Model for Wireless Energy Transfer, in ICDCN 2017.

Also in the Journal of Pervasive and Mobile Computing (PMC), 2017.

Limitations of the scalar model

- **Friis Model** (widely used):

$$P_r = P_t \times G_t \times G_r \times \left(\frac{\lambda}{4\pi R}\right)^2$$

  where G_t, G_r antenna gains, λ the wavelength and R the distance.
- It is a **scalar (1-dimensional) model**, assuming received is **additive**.
- A gross model, **unable to explain detailed phenomena** in real applications with many nodes:
  - **power cancellation** effects
  - **super-additive** received power
- Still, in case of one charger or few remote chargers, it is valid. When **"micro management"** is needed in the presence of **several nearby chargers**, then it is n**ot sufficient**.

A need for more precise models

- **Multiple nearby transmitters** introduce **complex interference** among waves.
- This leads to interesting **constructive and destructive** combinations of waves.
- This complex process necessitates the introduction of **vector (2-dimensional)** models, providing us with **more detailed and realistic** modeling abstractions.

Vector Model [2] (I)

- The **electric field** created by an energy transmitter (charger) C, operating at full capacity, at a receiver R at distance $d = \text{dist}(C, R)$ is given by

$$\mathbf{E}(C, R) \stackrel{def}{=} \sqrt{\frac{Z_0 \cdot G_C \cdot P_C}{4 \cdot \pi \cdot d^2}} \cdot e^{-j\frac{2\pi}{\lambda}d} \tag{4}$$

where Z_0 a constant for wave-impedance, G_C the antenna gain, P_C the transmitted power and λ the wavelength.

- This gives rise to a **2-dimensional vector**:

$$\mathbf{E}(C, R) \stackrel{def}{=} \beta \cdot \frac{1}{d} \cdot e^{-j\frac{2\pi}{\lambda}d} = \beta \cdot \frac{1}{d} \cdot \begin{bmatrix} \cos\left(\frac{2\pi}{\lambda}d\right) \\ \sin\left(\frac{2\pi}{\lambda}d\right) \end{bmatrix}, \tag{5}$$

where β constant depends on hardware and environment.

[2] M. Y. Naderi, K. R. Chowdhury, S. Basagni, Wireless sensor networks with RF energy harvesting: Energy models and analysis, in WCNC 2015

Vector Model (II)

- The **total electric field** at a receiver R created by a **family of energy transmitters** $\mathcal{C}$ is the **superposition (vector-sum)** of their individual electric fields, that is

$$\mathbf{E}(\mathcal{C}, R) \stackrel{def}{=} \sum_{\mathbf{C} \in \mathcal{C}} \mathbf{E}(C, R). \tag{6}$$

- Furthermore, the **total available power** at the receiver R is given by

$$P(\mathcal{C}, R) = \gamma \cdot \|\mathbf{E}(\mathcal{C}, R)\|^2, \tag{7}$$

where $\| \cdot \|$ denotes the **length (2-norm)** of the vector and γ constant depends on hardware.

Interesting Phenomena (I) - how two nearby points can differ a lot

- This model allows capturing **superadditive, cancellative interactions** of energy waves.
- An example:

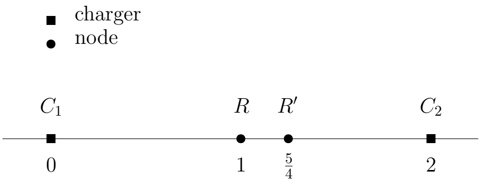
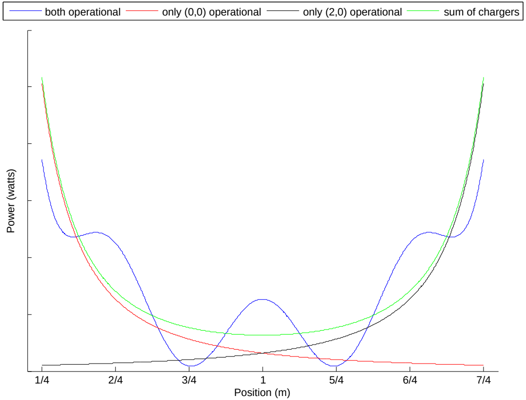


Figure: Chargers and nodes on a straight line.

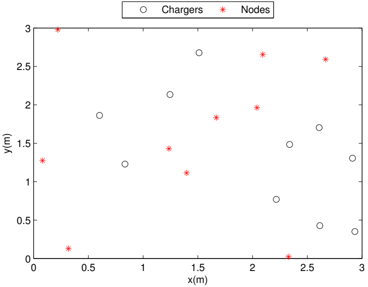
- $P(C_1, R) = P(C_2, R) = 1$ (only 1 transmitter operational).
- $P(\{C_1, C_2\}, R) = (\mathbf{1} + \mathbf{1})^{\mathbf{2}} > \mathbf{2}$ (both operational $\Rightarrow$ **superadditive** power since C_1, C_2 are equidistant and vectors have same direction).
- $P(\{C_1, C_2\}, R') = \left(\frac{8}{15}\right)^2 \approx 0.28 < \min\{P(C_1, R'), P(C_2, R')\} = \left(\frac{4}{5}\right)^2 \approx 0.64$ (**cancellation** effect at a nearby point).

Interesting Phenomena (II) - the full curves



- **Local maxima** indicate points of **superadditive** power.
- **Local minima** occur at points of **cancellation**.
- **Note**: It is highly **non-trivial to derive a closed formula** for the points of maximum/minimum power. So we have to examine **a whole space of system configurations** and evaluate power received.

A more general demonstration



- **10 chargers, 10 nodes** in a 3x3 area
- **all chargers turned on** $\Rightarrow$ max total received power $= 0.217W$
- **we switch off 2 chargers** $\Rightarrow$ max total received power $= 0.230W$ (because of **cancellative** interferences).

A real experiment [3]

Harvesting power (mW)/Distance to charger 2 (m)	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1
Charger 1	6.48	6.48	6.48	6.48	6.48	6.48	6.48	6.48
Charger 2	3.21	1.92	1.96	0.09	0.71	0.33	0.35	0.06
Charger 1 and Charger 2	3.57	2.05	3.47	7.78	2.11	1.32	9.04	6.04
Scalar model (Friis)	9.69	8.40	8.44	6.57	7.19	6.81	6.83	6.54
Vector model	6.21	5.11	8.19	6.58	5.77	6.62	6.74	6.42
Relative error of scalar model (Friis)	6.12	6.35	4.97	-1.21	5.08	5.49	-2.21	0.14
Relative error of vector model	2.64	3.06	4.72	-1.2	3.66	5.3	-2.3	0.02

Table: Charging power of two chargers.

- 2 chargers, 1 node at fixed distance 0.3m from charger 1, while the distance from charger 2 varies from 0.4m to 1.1m.
- 4th row: **actual power** measured
- 5th - 6th rows: **Friis, Vector estimation** of power
- last 2 rows: **relative errors** in each case

⇒ the **vector model** approaches the actual measurements **much better** than the scalar model.

[3] Y. Li, L. Fu, M. Chen, K. Chi, Y. H. Zhu, RF-based charger placement for duty cycle guarantee in battery-free sensor networks, IEEE Communications Letters 19 (10) (2015)

The notion of Configuration of Chargers

- consider a system of a family C of chargers and a family R of receivers (nodes).
- for each charger $c \in C$, let $\mathbf{x_c} \in [\mathbf{0}, \mathbf{1}]$ **a variable determining the "level of operation" of C** e.g. $x_c = 1$ means that C is fully operational (i.e., it operates at 100% capacity), while $x_c = 0$ means that C is switched off, and so on.
- The **received power** at a receiver R created by charger C operating at level x is the vector:

$$\mathbf{P}(C_x, R) = x_c \cdot \mathbf{E}(C, R) = x_c \cdot \beta \cdot \frac{1}{dist(C, R)} \cdot e^{-j \cdot \frac{2\pi}{\lambda} \cdot dist(C,R)} \tag{8}$$

- the **vector** $\mathbf{x_c} \in [\mathbf{0}, \mathbf{1}]^{\mathcal{C}}$ is called the **configuration** of the chargers.

Two power optimization problems (I)

Definition (MAX-POWER)

Given a family of chargers C and family of receivers $\mathcal{R}$, **find a configuration for the chargers that maximizes the total power** to $\mathcal{R}$. That is, find $\mathbf{x}^*$ such that

$$\mathbf{x}^* \in \arg \max_{\mathbf{x} \in [0,1]^C} P(C(\mathbf{x}), \mathcal{R}), \tag{9}$$

where $P(\mathcal{C}(\mathbf{x}), \mathcal{R}) = \sum_{R \in \mathcal{R}} P(\mathcal{C}(\mathbf{x}), R)$.

Two power optimization problems (II)

Definition (MAX-kMIN-GUARANTEE)

Given a family of chargers $\mathcal{C}$ and a family of receivers $\mathcal{R}$, **find a configuration for the chargers** that **maximizes the minimum cumulative power among all subsets of** $\mathcal{R}$ **of size k**. That is, find $\mathbf{x}^*$ such that

$$\mathbf{x}^* \in \arg \max_{\mathbf{x} \in [0,1]^{\mathcal{C}}} \min_{A \in \binom{\mathcal{R}}{k}} P(C(\mathbf{x}), A), \tag{10}$$

where $P(C(\mathbf{x}), A) = \sum_{R \in A} P(C(\mathbf{x}), R)$.

Obviously, this problem is a **generalization** of the MAX-POWER problem.

MAX-POWER can be expressed as a quadratic program

The MAX-POWER problem can be expressed as a **quadratic program**. For each $R \in \mathcal{R}$, define $\mathbf{Q}^{(R)}$ be a $2 \times m$ matrix whose j-th column is the 2-dimensional vector of the electric field created from C_j at R, i.e. $\mathbf{Q}^{(R)}_{:,j} = \sqrt{\gamma} \cdot \mathbf{E}(C_j, R)$, for each $j \in [m]$.

$$
\begin{aligned}
P(\mathcal{C}(\mathbf{x}), R) &= \gamma \|\mathbf{E}(\mathcal{C}(\mathbf{x}), R)\|^2 = \gamma \left\| \sum_{C \in \mathcal{C}} \mathbf{x}_C \mathbf{E}(C, R) \right\|^2 \\
&= \left(\sum_{C \in \mathcal{C}} \mathbf{x}_C \sqrt{\gamma} \mathbf{E}(C, R) \right)^T \left(\sum_{C \in \mathcal{C}} \mathbf{x}_C \sqrt{\gamma} \mathbf{E}(C, R) \right) = (\mathbf{Q}^{(R)} \mathbf{x})^T \mathbf{Q}^{(R)} \mathbf{x},
\end{aligned}
$$

Therefore, setting $\mathbf{H} \stackrel{def}{=} \sum_{R \in \mathcal{R}} \left(\mathbf{Q}^{(R)}\right)^T \mathbf{Q}^{(R)}$, the solution to MAX-POWER is given by

$$\mathbf{x}^* \in \arg \max_{\mathbf{x} \in [0,1]^m} \mathbf{x}^T \mathbf{H} \mathbf{x}.$$

Note:

- In general, quadratic problems **cannot be solved** in polynomial time.
- However, in our case, **special properties apply**, so we are able to provide **an efficient algorithm**.

Towards an Algorithm for MAX-POWER

We first provide the following lemma, which significantly **reduces the size of the search space** (which however is exponential).

Lemma

There exists **an optimal solution** $\mathbf{x}^*$ *to MAX-POWER in which each charger* **either operates at full capacity or not at all**, *i.e.*, $\mathbf{x}^* \in \{\mathbf{0}, \mathbf{1}\}^{\mathbf{m}}$.

Algorithm for MAX−POWER - A nice property

We can also prove a nice property:

Theorem

A configuration $\mathbf{x}^* \in \{0,1\}^m$ *is an optimal solution to MAX−POWER* **if and only if** $P(\mathcal{C}(\mathbf{x}^*),\mathcal{R}) \geq P(\mathcal{C}(\mathbf{y}),\mathcal{R})$, *for each* $\mathbf{y}$ *that comes from* $\mathbf{x}$ *by* **setting exactly one of its coordinates to either 0 or 1**.

- This property suggests that **any local maximum** of the objective function is also a **global maximum** that belongs to $\{0,1\}^m$.
- The above Lemma and Theorem suggest that **a distributed algorithm** (which we call **IterativeMaxPower**) can be used to find an **exact optimum configuration** for MAX−POWER.

The `IterativeMaxPower` Algorithm

- We begin from an arbitrary configuration in $\{0,1\}^m$.
- In each step, we parse the set of chargers in order to find a charger $C \in \mathcal{C}$ such that the total power received by R can be increased **by flipping** the operation level of C.
- The algorithm terminates if there is **no such charger** C.

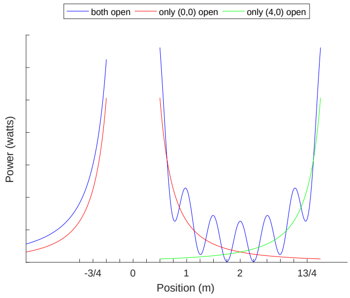
Theorem

`IterativeMaxPower` finds **an optimal solution** *to MAX-POWER in* $O\left(\frac{1}{\delta(C,R)} \cdot n \cdot m^5\right)$ *time, where* δ *a constant depending on the configuration.*

Algorithms for MAX-kMIN-GUARANTEE (I)

In this case, **Lemma 1 does not hold** and **fractional power levels achieve better performance** than $\mathbf{x} \in \{0,1\}^m$ as shown in the example:

(a) Chargers and nodes placement on a straight line.



(b) The power distribution between the two chargers. Different curves represent different operation levels of the chargers.

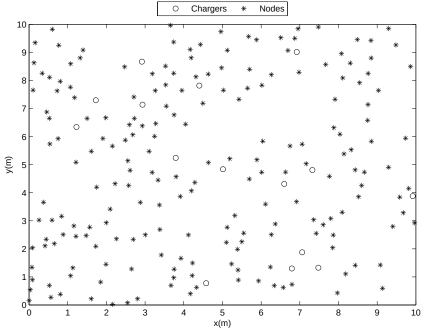
- C_1 is ON: $P(C_1, R_1) = (\frac{4}{3})^2 = 1.77$, $P(C_1, R_2) = (\frac{4}{13})^2 = 0.094$.
- C_2 is ON: $\min\{P(C_2, R_1), P(C_2, R_2)\} = (\frac{1}{4})^2 = 0.0625$.
- Both are ON: $P(\{C_1, C_2\}, R_1) = (\frac{4}{3} + \frac{4}{19})^2 = 2.38$ and $P(\{C_1, C_2\}, R_2) = (\frac{4}{3} - \frac{4}{13})^2 = 1.025$.

Algorithms for MAX-kMIN-GUARANTEE (II)

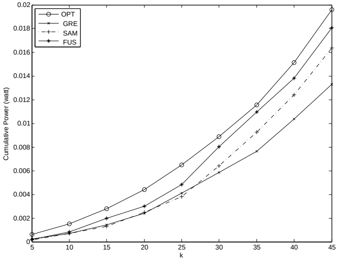
In view of the above **hardness** indication, we consider **a relaxation** of MAX-kMIN-GUARANTEE in which we only consider **optimal configurations in $\{\mathbf{0}, \mathbf{1}\}^{\mathbf{m}}$**, when each charger is either full operational or does not operate.

Performance Evaluation

The system we consider for the performance evaluation consists of chargers and nodes randomly deployed in a square field of 10m x 10m. **The number of chargers and nodes is set to 15 and 200** respectively.



Cumulative Power for MAX-kMIN-GUARANTEE Problem



Algorithm	**Assumption**	**Knowledge**	**Running Time**	**Performance**
Greedy	Initiate from a random configuration for chargers	checks all the nodes of the network	Fast	Low
Sampling	Initiate with σ different configuration, optimal for each sample	checks only the nodes of the sample	Average	Low for small k, Average
Fusion	Initiate with n different configuration, optimal for each node	checks all the nodes of the network	Slow	High

Table: Summary Table

- **Good approximation** of the optimum.
- The three heuristics achieve **different trade-offs** between running time and performance.

3. Peer to Peer Wireless Energy Exchange

- S. Nikoletseas, T. Raptis, C. Raptopoulos, Energy Balance with Peer-to-Peer Wireless Charging, 13th IEEE International Conference on Mobile Ad hoc and Sensor Systems, Brasilia, Brazil, in MASS 2016.

- A. Madhja, S. Nikoletseas, C. Raptopoulos and D. Tsolovos, Energy Aware Network Formation in Peer-to-Peer Wireless Power Transfer, in MSWiM, 2016.

Also in the Journal of Ad Hoc Networks 2017.

An emerging application: wireless power transfer in populations of weak devices

- Current approaches: strong computational and communicational WPT capabilities
- Also, they assume single-directional energy transfer from special chargers to the network nodes
- **Question:** What about populations of weak devices that have to operate under severe limitations in their computational power, data storage, quality of communication and most crucially, their available amount of energy? Example: Passively mobile finite state sensors, RFIDs, smart tags.
- Devices can achieve bi-directional, efficient wireless power transfer and be used both as transmitters and as receivers[4][5]
- Can they efficiently perform **network formation** of certain **energy distribution**?

[4] A. Georgiadis et al., "**Energy-autonomous bi-directional Wireless Power Transmission (WPT) and energy harvesting circuit**" in IEEE MTT-S IMS, 2015

[5] Z. Popovic et al., "**X-band wireless power transfer with two-stage high-efficiency GaN PA/ rectifier**" in IEEE WPTC, 2015

The Model

- Consider a population of m mobile agents $\mathcal{M} = \{u_1, u_2, \ldots, u_m\}$

  Each one equipped with a *battery cell*, a *wireless power transmitter* and a *wireless power receiver*
- The configuration of agent u at time t is $t \geq 0 \rightarrow C_u(t) \stackrel{def}{=} (E_u(t), q_u(t), R_u(t))$
- Each agent u has **a state** from a set of states $\mathcal{Q}$.
- Any pair of agents $\{u, v\}$ is characterized by a connection state from a set of states $\mathcal{Q}' = \{0, 1\}$.
- When two agents happen **to meet**, they interact according to an interaction protocol $\mathcal{P}$.
- Interactions between agents are planned by a probabilistic scheduler.
- **At each time step a single pair** of interacting agents is selected among all $\binom{m}{2}$ pairs.
- In interactions with energy transfer energy loss β is induced. We take $\beta \sim N(0.2, 0.05)$.

The Metrics

- We define the structural distance of the population from **the target graph H** at time t as follows:
$$\delta_t^s(H, G_t) \stackrel{def}{=} \min_{G \sim G_t} H \triangle G, \tag{11}$$
where $\mathbf{H} \triangle \mathbf{G}$ **the hamming distance** between those graphs, the G_t is the population network at time t and the minimum is taken over all graphs G that are isomorphic to G_t.
- We define the energy distance of the population from the **target energy distribution** $\mathcal{E}^*$ at time t as follows:
$$\delta_t^e(\mathcal{E}^*, \mathcal{E}(t)) \stackrel{def}{=} \min_{\sigma \in \Sigma(m)} \frac{1}{2} \sum_{i=1}^{m} |\mathcal{E}_i^* - \mathcal{E}_{\sigma(u_i)}(t)|, \tag{12}$$
where the minimum is among all permutations of $[m]$, $\mathcal{E}_{\sigma(u_i)}(t)$ is the relative energy level of agent $\sigma(u_i)$ at time t and $\mathcal{E}_i^*$ is the target distribution at point i of its domain.

The problem

- Consider a **population** $\mathcal{M}$ of agents.
- Let H be a **target graph** on $\mathcal{M}$ and $\mathcal{E}^*$ a **target energy distribution**.
- Let ϵ be a small positive constant.
- Assume the probabilistic scheduler that selects the pairs of agents to interact.

Energy aware network formation

Design a protocol that, when ran by the agents in the population, there is $t \geq 0$ such that

- $\delta_t^s(H, G_t) = 0$
- $\delta_t^e(\mathcal{E}^*, \mathcal{E}(t)) \leq \epsilon$ and
- the total energy loss is minimized.

(a) Population Energy Balance Problem

Design an interaction protocol $\mathcal{P}$ that achieves approximate energy balance at the **minimum energy loss** across agents in $\mathcal{M}$.

(b) Energy Aware Star Formation Problem

Design an interaction protocol $\mathcal{P}$ that:

- constructs a global star topology and
- achieves an **energy distribution** where the energy level of each agent is proportional to its degree.

A variety of protocols

For each problem, we provide **several protocols** each one, achieving **different trade-offs** between performance and time complexity, network knowledge, agents memory.

4. Future Trends

- Ultra-fast battery charging technologies, towards increased scalability
- extend wireless range and charging efficiency via resonant repeaters
- hybrid approaches: ambient energy harvesting and wireless charging for setting up green networks
- wireless powered body area networks: different types of wearables and nano-sensors exchanging energy in a transparent, interoperable manner

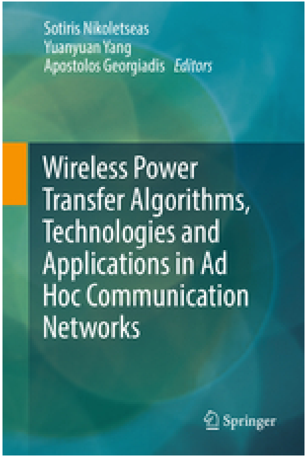
Collaborators

It is always a collective effort, with precious collaborators:

- Dr. **Christoforos Raptopoulos**
- Dr. **Theofanis Raptis**
- Dr. **Marios Angelopoulos**
- PhD student **Adelina Madhja**
- PhD student **Ioannis Katsidimas**
- PhD student **Dimitrios Tsolovos**

New Book

S. Nikoletseas, *Y. Yang* and *A. Georgiadis*, **Wireless Power Transfer Algorithms, Technologies and Applications in Ad Hoc Communication Networks**, Springer Verlag, 2016.



Book Themes

T1. Technologies
T2. Communication
T3. Mobility
T4. Energy Flow
T5. Joint Operations
T6. Electromagnetic Radiation Awareness