Power Sensor Networks by Wireless Energy: Current Status and Future Trends

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Outline

- Up-to-date review for current research status in wireless rechargeable sensor networks (WRSN)
  1. Efficient gathering of energy information
  2. Recharge scheduling under practical constraints
  3. Integration of wireless charging with data collection
- Some future directions
  1. Ultra-fast battery charging technology
  2. Extending wireless charging range
  3. Designing a green, autonomous, eco-friendly WRSN by combining energy harvesting and wireless charging

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- Background
- Related work
- Network architecture and basic principles
- Collect real-time energy information
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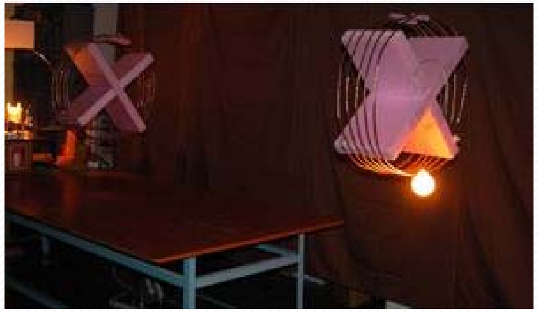
- Future directions
- Summary

Background

- Recently, wireless energy transfer opens up a new dimension in wireless sensor networks and becomes a game-changing technology to power sensors
- Pioneered by Tesla a century ago, recently the technology enjoys so much popularity due to work of Kurs et. al [1]
- Prototype from MIT lab



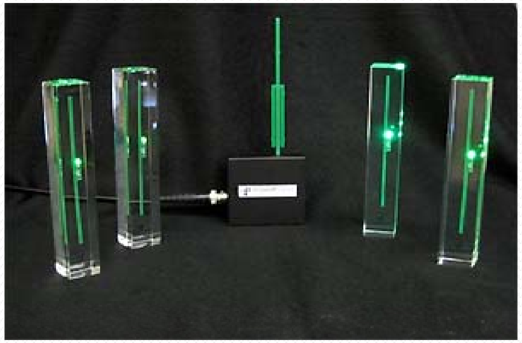
Transfer 40W over 2 meters

Through barriers between source and receiver

[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.

Background

- Wireless energy transfer provides more reliable and controllable energy source than environmental energy harvesting (e.g., solar, wind)
- Two basic wireless transferring techniques:
  - Electromagnetic radiation: low charging efficiency, only support low-power devices, charging distance up to 1-3 m
  - Resonant magnetic coupling: high charging efficiency, support high-power equipment (e.g., electrical vehicle), charging distance < 1 m



Electromagnetic radiation Products from Powercast Corp.

Resonant magnetic coupling charges electrical vehicle.

Background

- A wireless sensor network powered by wireless power transfer is referred to as **wireless rechargeable sensor network (WRSN)**
- Radiation-based wireless charging only provides very limited charging capability. It has to operate under FCC regulations of 4W emission power
- Resonant magnetic coupling is more desirable. It requires a mobile vehicle equipped with a charging device to move around the field, and recharge sensors in close distance
- We focus on resonant magnetic coupling based wireless charging

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Related Work (Radiation-Based)

- Placement of wireless chargers in the network to sustain network operation and minimize recharge latency [2,3]
- Impact of wireless charging on routing and deployment in sensor networks [4]
- An O(k^2 k!) (k: # nodes) algorithm for scheduling recharge activities to maximize network lifetime [5]
- Safety issue: Placement of wireless chargers such that no locations expose excessive wireless radiations [6]

- [2] S. He, J. Chen, F. Jiang, D. Yau, G. Xing and Y. Sun,"Energy provisioning in wireless rechargeable sensor networks," IEEE Trans. Mobile Computing, vol. 12, no. 10, pp. 1931-1942, Oct. 2013.
- [3] L. Fu, P. Cheng, Y. Gu, J. Chen and T. He, "Minimizing charging delay in wireless rechargeable sensor networks," IEEE INFOCOM, pp. 2922-2930, 2013.
- [4] B. Tong, Z. Li, G. Wang and W. Zhang, "How wireless power charging technology affects sensor network deployment and routing," IEEE ICDCS, 2010.
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- [6] H. Dai, Y. Liu, G. Chen, X. Wu and T. He,"Safe charging for wireless power transfer," IEEE INFOCOM, 2014.

Related Work (Resonant Magnetic Coupling)

- Optimization to maximize the ratio of charging vehicle's idle time over working time [7]
- Joint optimization of mobile data collection and energy charging by a single vehicle [8,9]. It first determines nodes for recharge and plans the shortest route while guaranteeing a bounded tour length
- Protocol for real-time energy status info collection [10,11], and online charging algorithms were proposed based on most updated energy information in the network
- Some practical constraints, such as vehicle's recharge capacity, moving cost and node's dynamic lifetime were considered together in optimization [12]

Reference

- [7] Y. Shi, L. Xie, T. Hou and H. Sherali, "On renewable sensor networks with wireless energy transfer," IEEE INFOCOM, 2011.
- [8] S. Guo, C. Wang and Y. Yang, "Joint mobile data gathering and energy provisioning in wireless rechargeable sensor networks," IEEE Trans. Mobile Computing, 2014 (IEEE INFOCOM '13).
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- [12] C. Wang, J. Li, F. Ye and Y. Yang, "Recharging schedules for wireless sensor networks with vehicle movement costs and capacity constraints," IEEE SECON, 2014.

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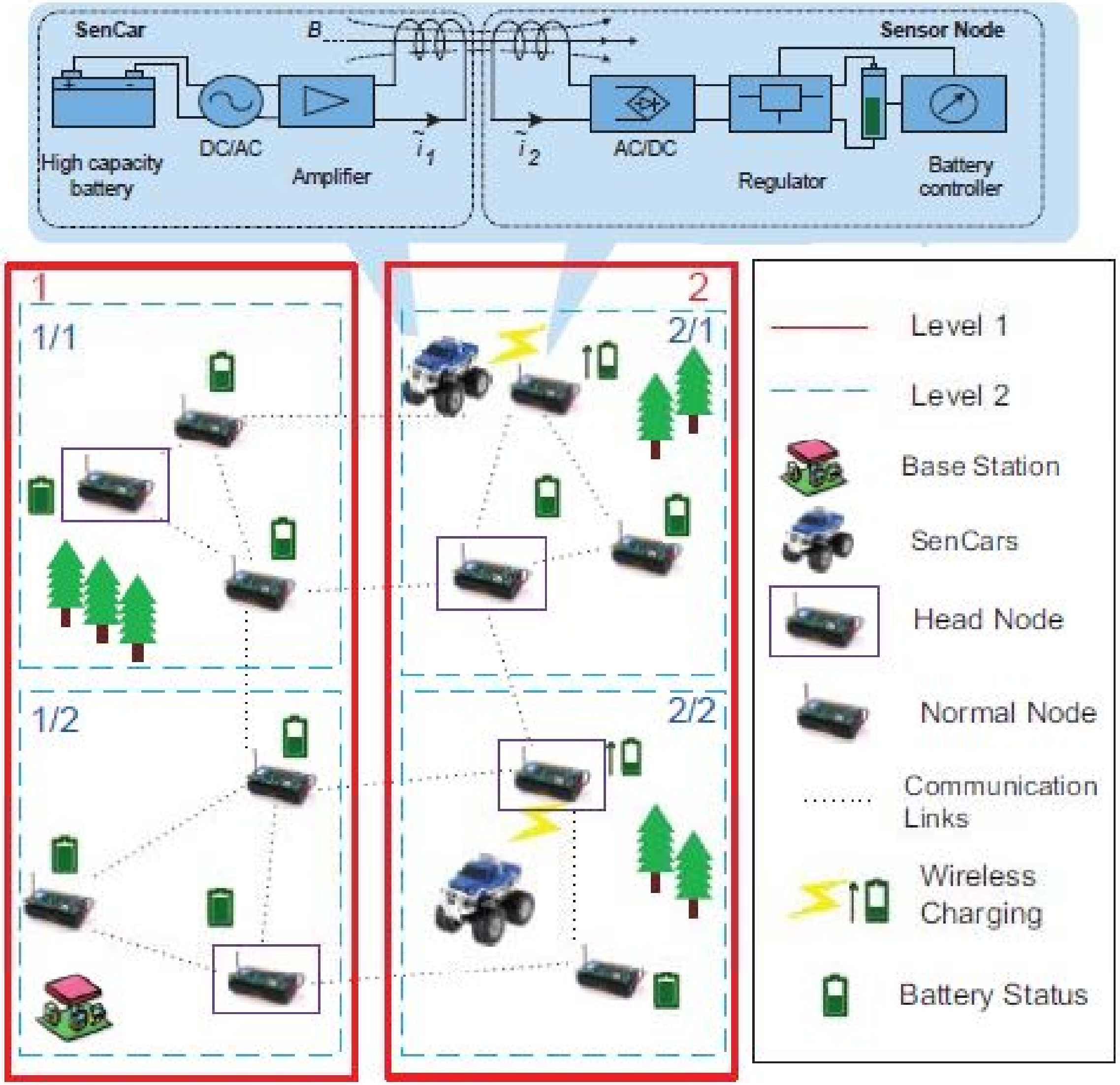
Basic Components in WRSN



Area: Geographical organization of nodes, hierarchically divide network into different areas

SenCar: Multi-functional vehicle carrying charging coils with powerful battery

Head node: aggregates energy information from each sub-area

Base station: provides maintenance and support, commands the SenCar

Basic Principles for WRSN

- To achieve perpetual network operation, energy neutral condition must hold:
- $E(T) < R(T) + E\_I$
- For any arbitrarily long time period, energy consumed in the network *E(T)* should be less than energy recharged into the network plus initial energy *E_I* from all nodes
- Question: What is the minimum number of SenCars required to maintain energy neutral condition?

Basic Principles for WRSN

- How to calculate the number of SenCars required [11]
- Estimate an upper bound of R(T) when SenCars keep recharging sensor nodes without any idle time. R(T) depends on the recharging rate of sensor's battery
- E(T) can be approximated by a Gaussian random variable by computing its mean $\overline{\boldsymbol{E}(\boldsymbol{T})}$ and variance $\boldsymbol{\sigma}^2(\boldsymbol{T})$ from the aggregated energy consumption pattern from sensors.
- Energy neutral condition holds with probability:

$$\boldsymbol{P} = \phi\left(\frac{\boldsymbol{R}(\boldsymbol{T}) + \boldsymbol{E}_0 - \overline{\boldsymbol{E}(\boldsymbol{T})}}{\sqrt{\boldsymbol{\sigma}^2(\boldsymbol{T})}}\right)$$

Basic Principles for WRSN

- Probability P ≈ 1 means energy neutral condition always holds
- Probability 1 requires Gaussian variable to approach infinity
- Consider energy neutral condition holds at probability very close to 1, e.g., P = 0.99
- Calculate number of SenCars required, m

$$\boldsymbol{m} = \left\lceil \frac{\Phi^{-1}(0.99)\boldsymbol{\sigma}(\boldsymbol{T}) + \overline{\boldsymbol{E}(\boldsymbol{T})} - \boldsymbol{E}_0)(\bar{\boldsymbol{d}}/\boldsymbol{v} + \boldsymbol{t}_r)}{\boldsymbol{C}_b \boldsymbol{T}} \right\rceil$$

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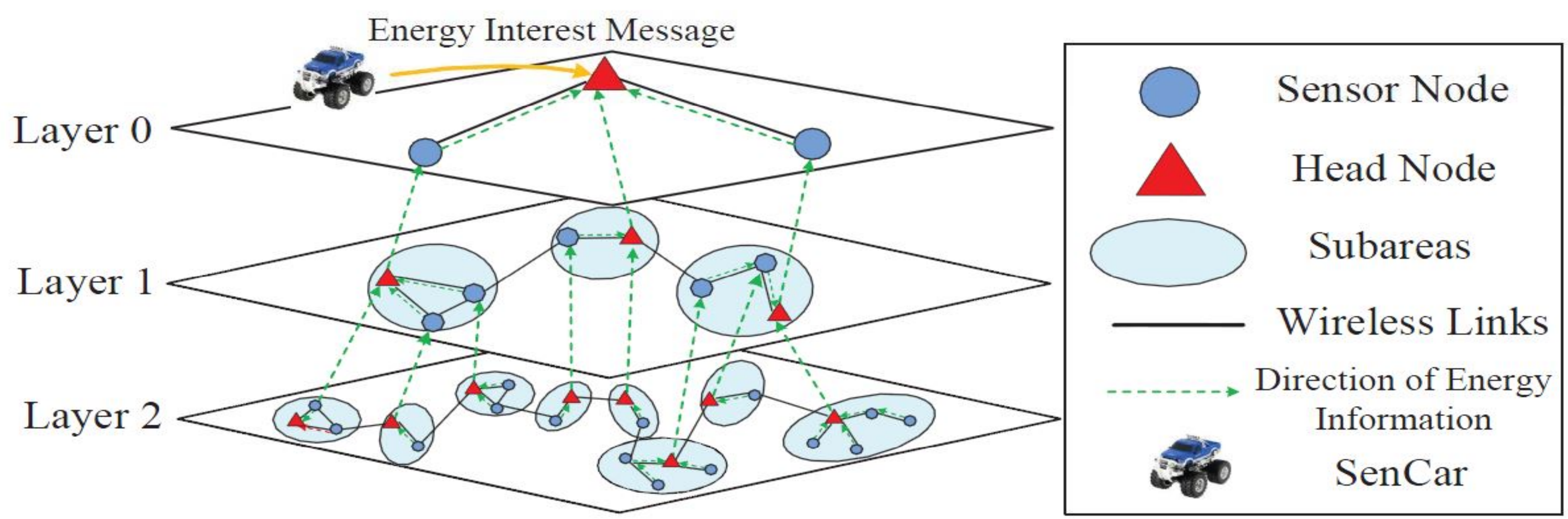
Recharge Scheduling – Collect Energy Info

- Gathering real-time energy status info is critical for decision making in recharge scheduling
- All previous works ignored when and how energy info is collected
- Due to dynamics of the network (sudden drop of energy level due to external events), overlooking energy info could lead to inaccurate recharge decisions
- For example, recharging a sequence of 10 nodes may require at least 10 hours for Ni-MH batteries, energy on sensor nodes may change dramatically during this period

Recharge Scheduling – Collect Energy Info



Operations:

1. SenCar sends energy info requesting message (interest)
2. Head nodes on each level receive and propagate the interest message until the bottom level is reached
3. Bottom level nodes receiving interest respond with their energy info (data)
4. Energy info message propagates along the head hierarchy until SenCar is reached

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Recharge Scheduling

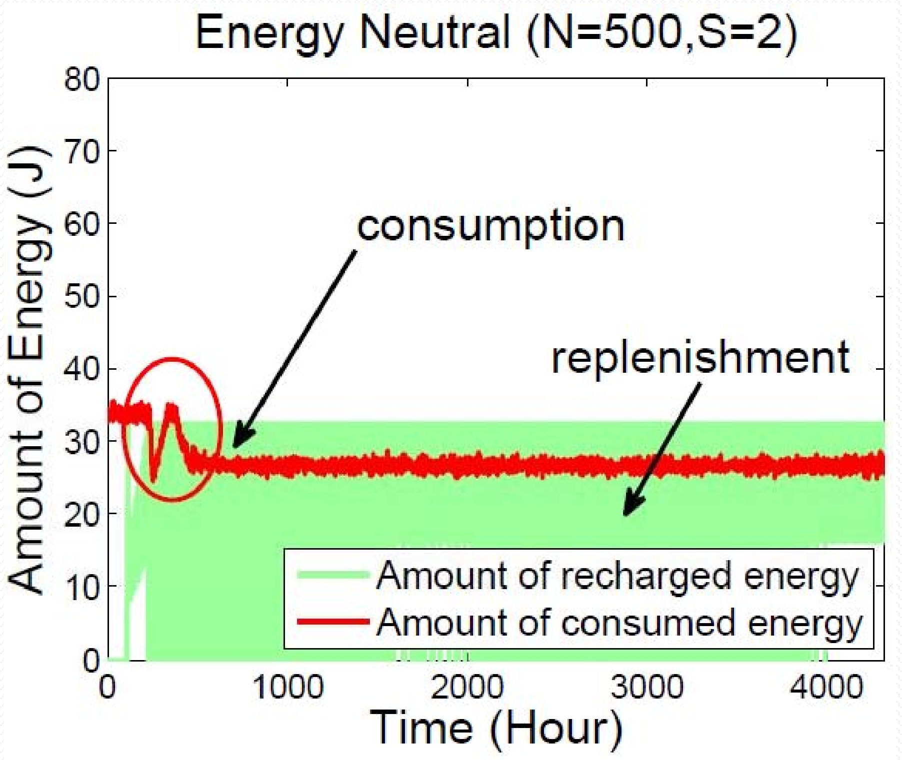
- Objective: Minimize total traveling cost on SenCars and maintain perpetual network operation (i.e., no sensor depletes energy)
- Which node to select next for recharge?
- A weighted-sum online algorithm [11]:
  - Select next node with minimum weighted-sum w_i:
  - $w_i = a L_i + (1-a) t_i$
  - L_i is the residual lifetime of node i, t_i is the traveling time of SenCar from its current position to node i's position
  - Vary weight parameter *a* and select a node with the least weight value

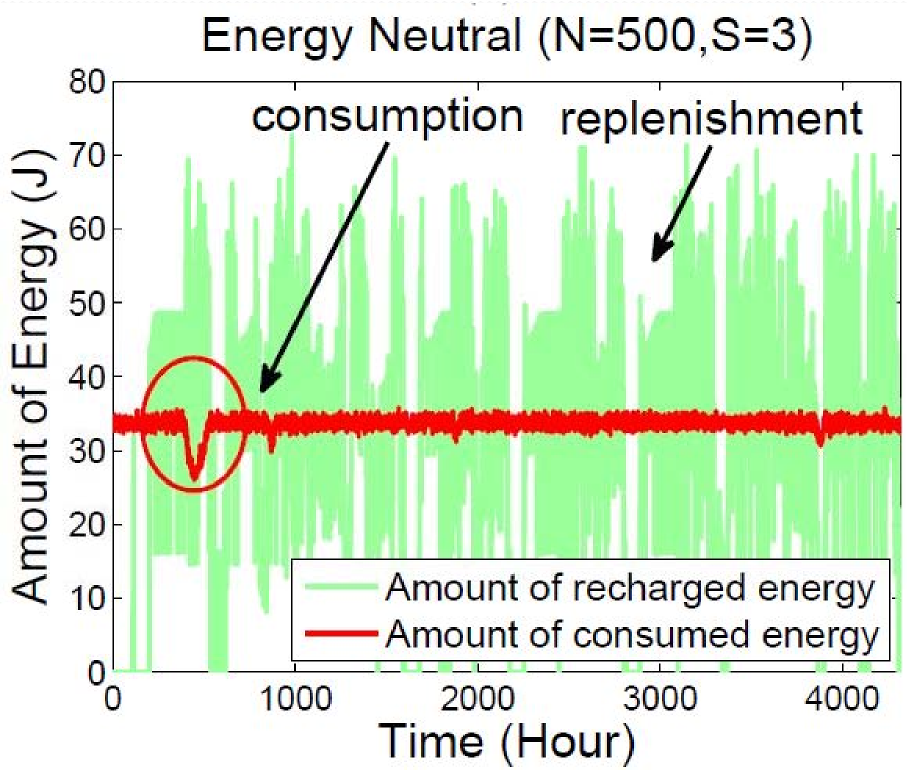
Weighted-Sum Algorithm

- Try different weighted parameters, and select the best route with the lowest cost
- SenCars communicate among themselves via long range radio to cooperatively compute weighted sum
- Avoid choosing the same node to recharge
  - Each time a node is selected, SenCar reports to *Base Station* (node will be released after finish recharging)
  - Each time before SenCar recharges a node, it checks with *Base Station* if the node is available

Evaluation of Weighted-Sum Algorithm

- Trace of energy consumption and replenishment
- 500 nodes, 2 and 3 SenCars
- Theoretical results: $S = \lceil 2.41 \rceil = 3$
- At least 3 SenCars are needed for perpetual operation





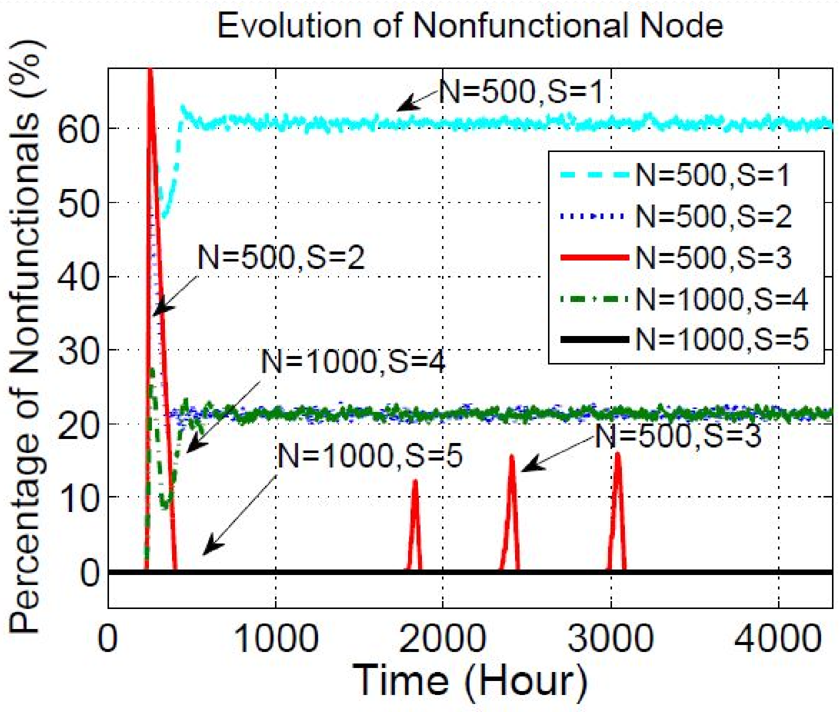
Evaluation of Weighted-Sum Algorithm

- Observations:

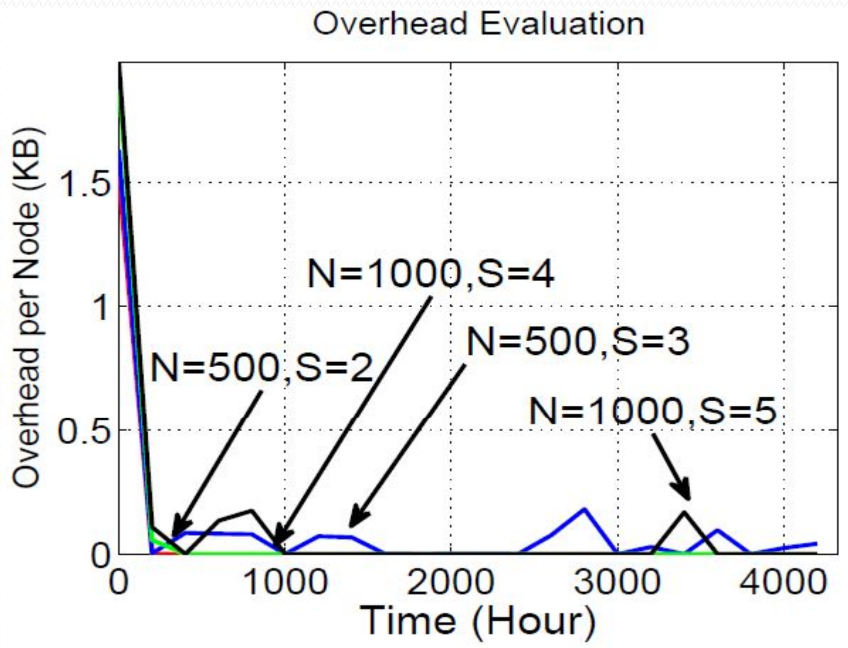
1. Left Fig: 2 SenCars are not enough. Energy consumption curve steps down around 500 hours, because some nodes deplete energy, and later on, SenCars are not able to restore the energy level on these nodes so the consumption curve stays below the replenishment curve
2. Right Fig: 3 SenCars are enough. Energy consumption curve also steps down but soon recovered at 500 hours, because nodes are restored by SenCar, showing 3 SenCars can handle 500 nodes for perpetual operation

Evaluation of Weighted-Sum Algorithm

- Evaluate nonfunctional nodes for 500, 1000 nodes.
- N=500, S=3; N=1000, S=4 are threshold cases for perpetual operation
- In simulation set-up phase, more overhead (messages) is observed. Bursts due to head re-selections



Nonfunctional nodes



Overhead evolution

Recharge Scheduling – Practical Constraints

- Previous work assumed the moving of SenCar is free and SenCar has infinite energy capacity
- Constraints of SenCar's recharge capacity, moving cost and node's dynamic lifetime are important in practice
- Bringing them all together into a recharge scheduling problem is difficult
- Formulate the problem into a *Profitable Traveling Salesmen Problem with Capacity and Battery Deadlines Constraints*
- Objective: Maximize total energy recharged into sensors minus energy cost on SenCars
- NP-hard problem (reduced to classic Traveling Salesmen Problem)

Recharge Scheduling -Practical Constraints (Formulations)

Objective: maximize recharge profits (recharge energy minus moving cost) →

$$\mathbf{P1}: \quad \max \left\{ \sum_{a=1}^{m} \sum_{i=1}^{n_r} r_i y_{ia} - \sum_{i=1}^{n_r} \sum_{j=1}^{n_r} c_{ij} x_{ij} \right\} \tag{12}$$

Subject to

SenCar starts at origin and finishes at origin →

$$\sum_{j=1}^{n_r} x_{0j}^{(a)} = \sum_{i=1}^{n_r} x_{i0}^{(a)} = 1, \forall a = 1, 2, \ldots, m \tag{13}$$

Connectivity constraint, each vertex is visited once →

$$\sum_{i=1}^{n_r} x_{ik} = \sum_{j=1}^{n_r} x_{kj} = 1; \forall k = 2, \ldots, n_r \tag{14}$$

Capacity constraint →

$$\sum_{i=1}^{n_r} r_i y_{ia} \le C_a, \forall a = 1, 2, \ldots, m \tag{15}$$

Each node visited by one SenCar →

$$\sum_{a=1}^{m} y_{ia} = 1, \forall i = 1, 2, \ldots, m \tag{16}$$

Time constraint (arrival of SenCar before node's lifetime expires) →

$$A_i \le l_i; \forall i = 1, 2, \ldots, n_r \tag{17}$$

$$x_{ij} \in \{0, 1\}; \forall i, j = 1, 2, \ldots, n_r, \tag{18}$$

$$y_{ia} \in \{0, 1\}; \forall i = 1, 2, \ldots, n_r, \forall a = 1, 2, \ldots, m \tag{19}$$

Eliminate subtour →

$$2 \le u_i \le n_r; \forall i = 2, 3, \ldots, n_r \tag{20}$$

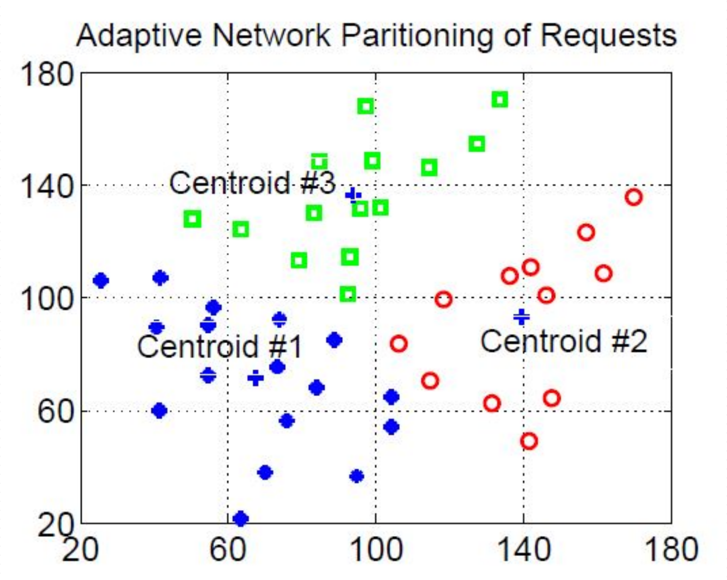
$$u_i - u_j + (n_r - m) x_{ij} \le n_r - m - 1 \quad \forall i, j = 2, 3, \ldots, n_r, i \ne j \tag{21}$$

Recharge Scheduling – Practical Constraints (Greedy Algorithm)

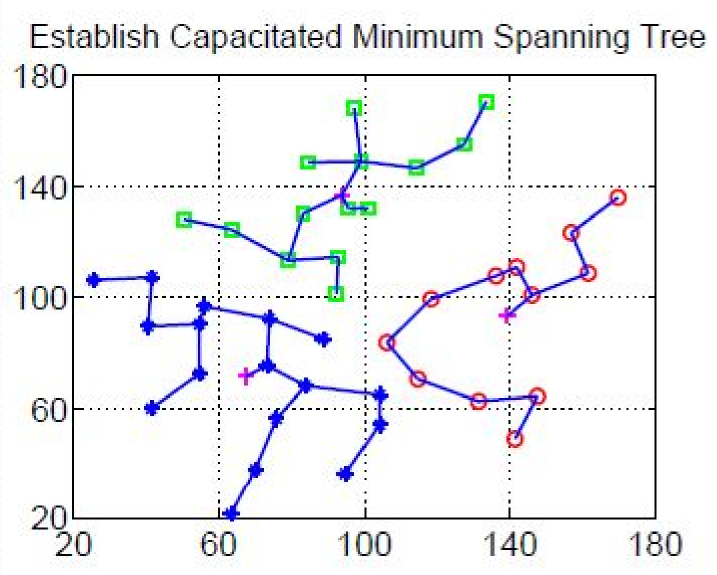
- A trivial *Greedy algorithm*: in each step, SenCars select the node with maximal recharge profit (recharged energy of node less energy cost moving to this node)
- SenCar returns to base station if its own battery is low
- Potential problem with the greedy approach:
  - It may cause SenCar to move back and forth in the field because each time it selects the node with maximal recharge profit. Moving energy cost would be high in this case
  - No guarantee to recharge nodes within their battery deadlines

Recharge Scheduling – Practical Constraints (3-Step Algorithm)

- 3-Step Adaptive Algorithm [12]:
- Step 1: Adaptive network partition and assign each SenCar to a region for recharge – avoid moving back and forth in the field
- Step 2: Construct Capacitated Minimum Spanning Tress in each region for SenCars



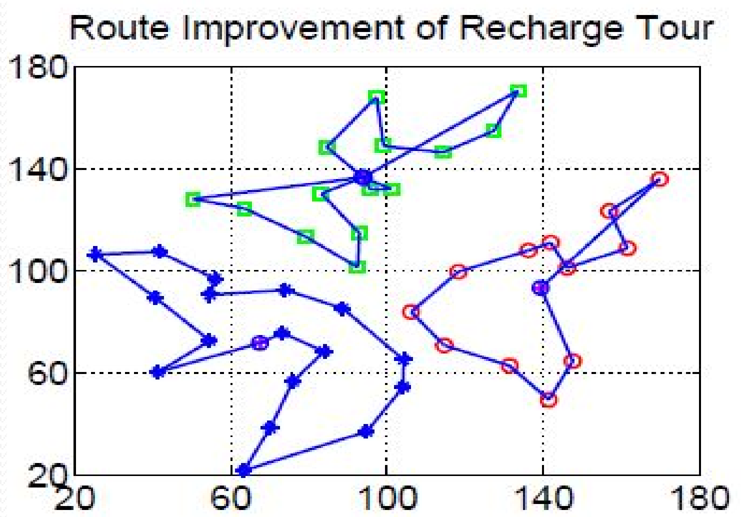
Step 1



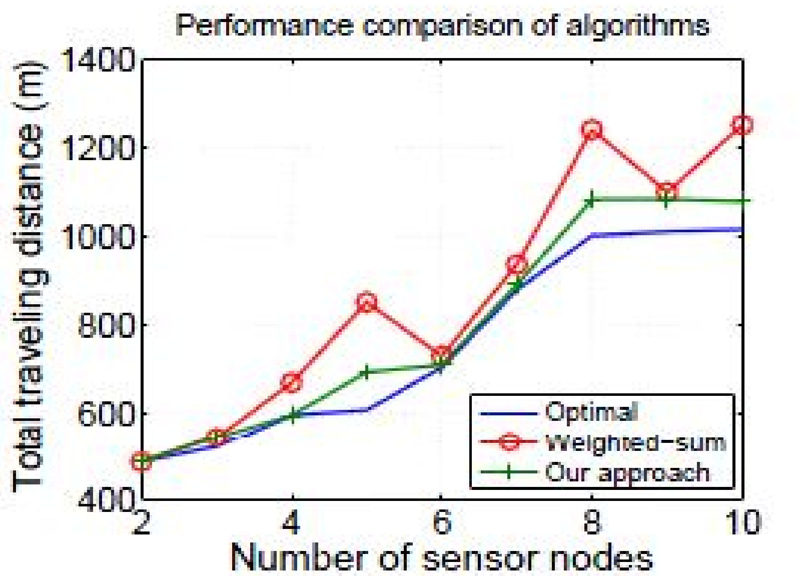
Step 2

Recharge Scheduling – Practical Constraints (cont'd)

- Step 3: Insert nodes that need prioritized recharge back into an established sequence of non-prioritized nodes - each insertion should capture node lifetime constraint
- Traveling cost comparison of weighted-sum algorithm, insertion-based adaptive algorithm and optimal solution
- Adaptive algorithm performs better than weighted-sum algorithm and is close to optimal algorithm

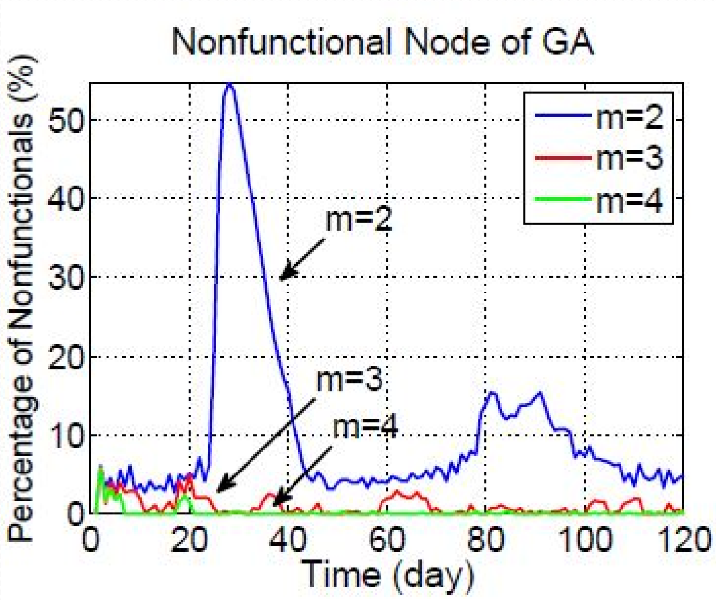


Step 3:

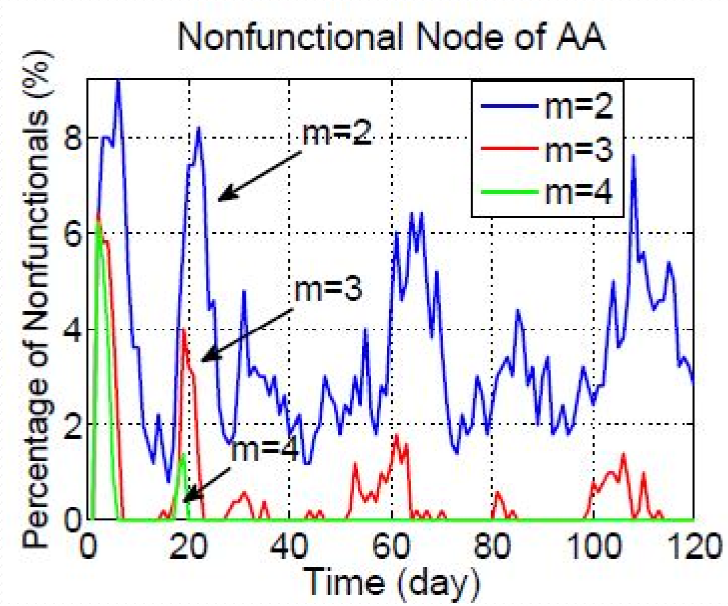


Performance of Recharge Algorithms

- *Greedy Algorithm(GA)*: when # SenCars m=2, 5-15% non-functional nodes. Big spike around 22 days due to recharge capability is temporarily exceeded when sensors request for recharge at the same time
- 3-step Adaptive Algorithm(AA): when m = 2, no spike is observed and nonfunctional node is < 10% all the time. When m = 4, AA can reduce nonfunctional nodes to zero



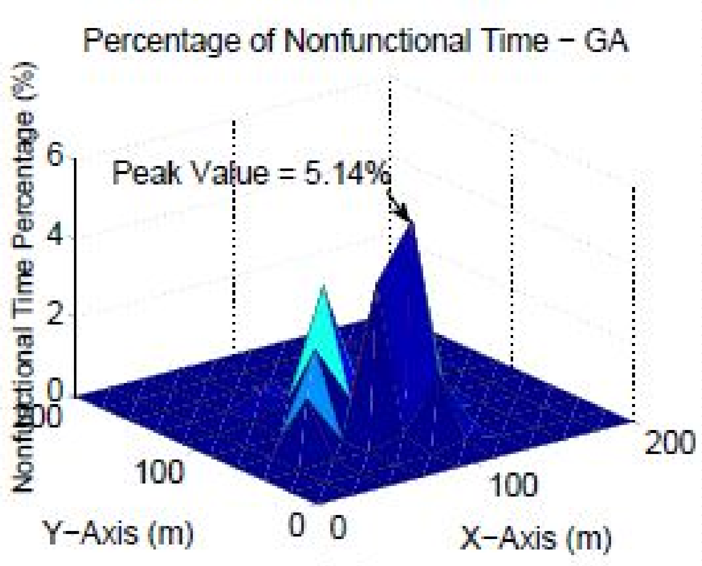
Greedy Algorithm

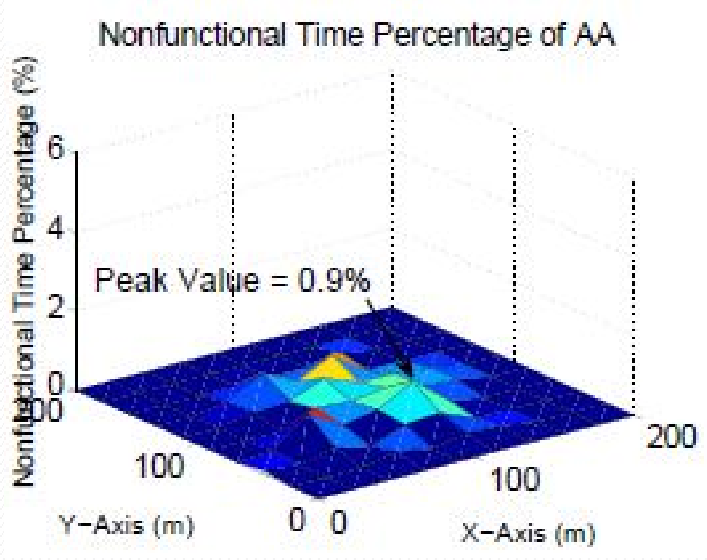


3 Step Adaptive Algorithm

Performance of Recharge Algorithms

- Compare percentage of time nodes are nonfunctional
- GA – nodes near base station have maximum of 5.14% time in nonfunctional status
- AA – nodes only have maximum 0.9% time in nonfunctional status
- AA also spreads nonfunctional nodes more evenly across the field than GA





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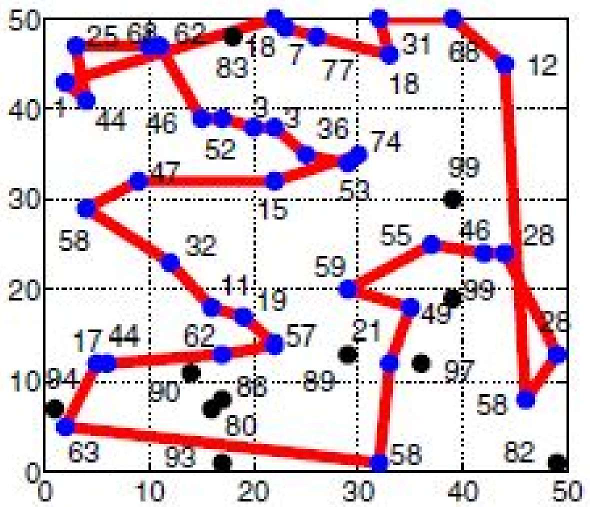
Integrate Wireless Charging with Data Collection

- Basic Idea: perform wireless charging and mobile data collection by the same SenCar [8,9]
- Advantage: Less manufacturing cost, human labor to command SenCar; mobile data gathering – uniform energy distribution; wireless charging – perpetual operation
- First, select *anchor points* where SenCar performs recharge and collects data from the neighborhood



Example of anchor point selection algorithm

Criteria: Select the nodes with the least energy and guarantee the recharge tour length is under a threshold

Integrate Wireless Charging with Data Collection

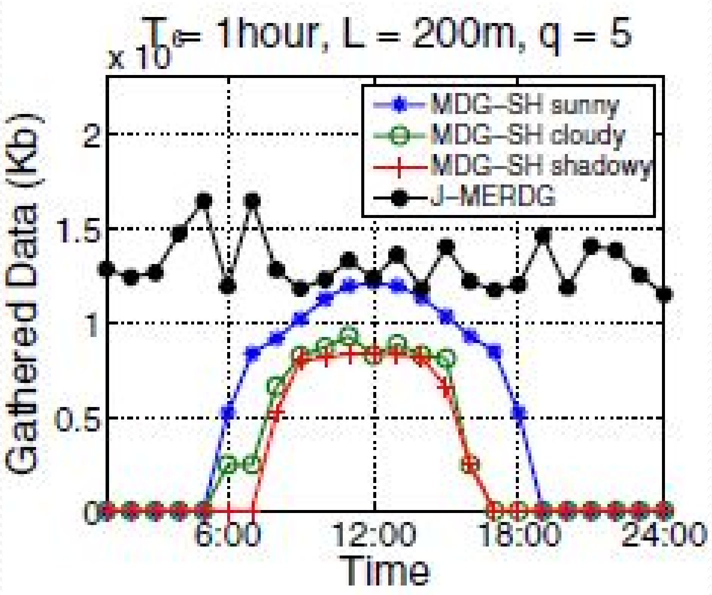
- After anchor points are selected, we need to optimize:
  - Data rates – sensors forward towards different anchor points
  - Link flows – determine link flow rates on different links under sensors' energy budget and link capacity
  - SenCar's sojourn time – how to allocate the time SenCar stops at different anchor points
- Formulate the problem into an optimization problem
- Objective: Maximize the overall utility on sensor nodes. Utility here refers to the amount of data uploaded from sensor nodes

Integrate Wireless Charging with Data Collection

- Use the well-known subgradient method [16] to solve the problem optimally – we can obtain an optimal solution given the selection of anchor points.
- Each sensor computes data rates and link flow routing in a distributed manner, and SenCar calculates how long it should stop at each anchor point
- There are two iterations, subgradient iteration (inner loop) and proximal iteration (outerloop)
- Subgradient iteration converges within 150 iterations and proximal iteration converges within 10 iterations

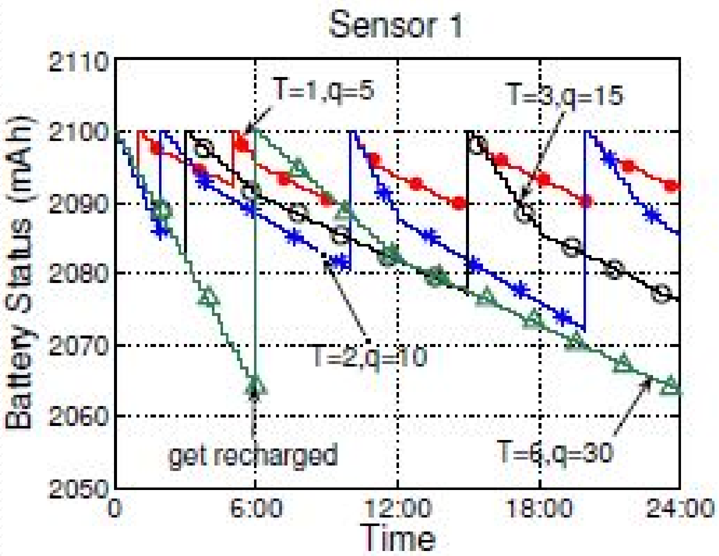
Integrate Wireless Charging with Data Collection

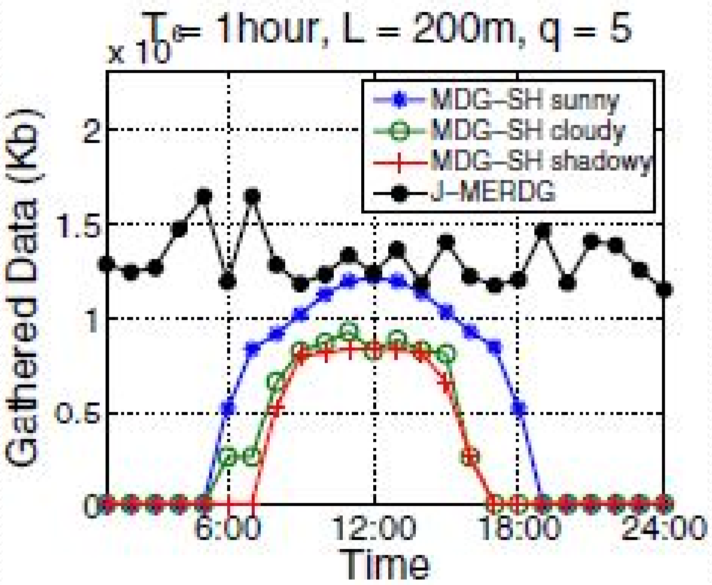
- A system-wide optimization is performed based on anchor points selected
- Each sensor computes data rates and link flow routing in a distributed manner
- Compare the amount of data gathered with solar harvesting in 24 hours: Wireless charging is not affected by weather dynamics



Wireless charging provides more reliable and stable service since solar harvesting cannot sustain network operation during night time.

Integrate Wireless Charging with Data Collection





- Trace of energy status

  Tracing energy evolution on a sensor. It shows the anchor point selection algorithm can accurately choose the node for recharge once its energy is low

- Wireless charging not affected by weather dynamics

  Evaluation compares amount of data gathered with solar harvesting techniques. Wireless charging techniques provides more reliable and stable service since solar harvesting cannot sustain network operation during night time

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Future Directions – Ultra-Fast Battery Charging

- Ultra-fast battery charging technology – researchers have used bio-organic fast charging technology to demonstrate fully charging an iphone battery in 30 seconds [13]

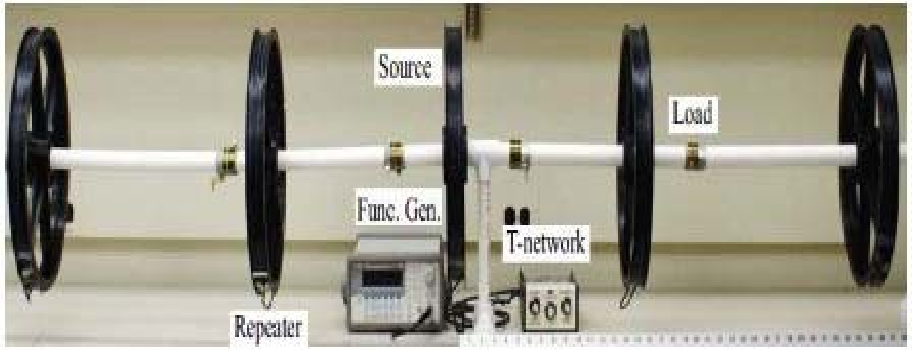
Example in [13]: Israel researchers demonstrate the latest fast charging technique

Future Directions – Ultra-Fast Battery Charging

- Compared to traditional battery (NiMH) that needs1-2 hours to charge, SenCars can cover hundreds of nodes in just a few hours
- Much higher scalability and efficiency
- It requires some revisions in the existing algorithms: with ultra-fast charging, SenCar's moving time will be the dominating factor other than recharge time

Future Directions – Extend Charging Range

- Extend wireless charging range and efficiency using resonant repeaters [14-15]
- SenCar can recharge multiple nodes simultaneously
- Advantage: higher temporal efficiency, SenCar can cover a larger network size

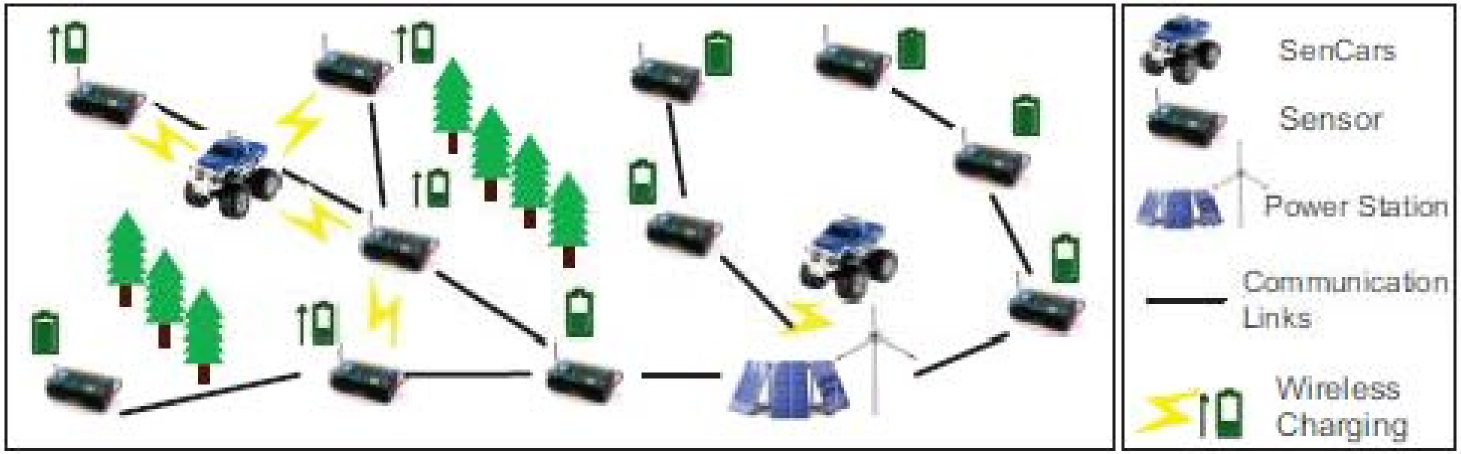


Distribute 15mW energy to 6 loads by 4 repeaters over 2 m [14]

Power a 14W lamp by organizing repeaters into domino form [15]

Future Directions – Echo-Friendly WRSN

- Designing echo-friendly WRSN
- How to provide energy sources for SenCar?
- A hybrid network structure combining energy harvesting and wireless charging
- SenCar periodically returns to base station for battery recharge. Base station is powered by ambient energy source such as solar, wind, etc.



Future Directions – Echo-Friendly WRSN

- Several interesting questions for this new network structure
- Where to place energy harvesting stations is a placement problem (high exposure to energy sources, easy access to SenCars)
- How to achieve balance between energy income and energy consumption
- How to minimize overall cost of network including sensor's energy consumption, SenCar's moving cost, charging cost, etc.

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- We have provided an up-to-date review for the current research status in wireless rechargeable sensor networks (WRSNs)
  1. Efficient and real-time gathering of energy status information
  2. Recharge scheduling problem (with practical constraints)
  3. Integration of wireless charging with mobile data collection
- We have also pointed out several future directions
  1. Ultra-fast battery charging technology
  2. Extending wireless charging range by repeaters
  3. Designing a green, autonomous, eco-friendly WRSN by combining energy harvesting and wireless charging

References

- [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.
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Thank you
Q&A

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