Wireless Rechargeable Sensor Networks - Current Status and Future Trends

Yuanyuan Yang, Cong Wang, and Ji Li
Department of Electrical and Computer Engineering, Stony Brook University, Stony Brook, NY, 11790 USA
Email: {yuanyuan.yang, cong.wang, ji.li}@stonybrook.edu

Abstract —Traditional battery-powered wireless sensor networks face many challenges to meet a wide range of demanding applications nowadays due to their limited energy. Although energy harvesting techniques can scavenge energy from the environment to sustain network operations, dynamics from the energy sources may lead to service interruption or performance degradation when the sources are unavailable. Recent advances in wireless energy transfer have opened up a new dimension to resolve the network lifetime problem. In this paper, we present an overview of the wireless energy transfer techniques and recent developments to apply them in various sensing applications. We also show how this novel technology can be integrated with typical sensing applications and envision future directions in this area.

Index Terms—Wireless sensor network, wireless energy transfer, perpetual operation, mobile data gathering

I. Introduction

With an increasing demand for diverse applications in our daily life, sensors have provided a bridge between the physical world and computer networks. By organizing sensor nodes into an autonomous network, Wireless Sensor Networks (WSNs) can sense, process and deliver information to enrich these data-driven applications. Such growing applications require more complex sensors so they usually have much higher energy consumption. To this end, energy conservation has been one of the primary focuses in the WSN research for the last decade [1]. These studies either try to optimize duty cycle on a single sensor or aim to maximize lifetime of the network [2], [3]. Although network lifetime can be elongated to some extent, battery-powered sensor nodes would deplete energy eventually. Replacing their batteries may require extensive human efforts especially in hazard circumstances such as detecting forest fire or monitoring volcano activities [4], [5]. If sensor's battery energy can be renewed, network lifetime can be extended towards perpetual operations.

Recently, environmental energy harvesting has been proposed to renew sensor's battery. By installing external devices such as solar panels and wind turbines, sensors can scavenge ambient energy [6]–[8]. However, inherent dynamics in the ambient energy sources can greatly impact network utilization and cause intermittent service interruptions when the energy sources are unavailable. Thus, finding a reliable way to replenish sensor's battery starts to attract more attention in the sensor network research community.

Fortunately, the latest breakthroughs in wireless energy transfer technology have provided a revolutionized way to power devices in distance without wires or plugs. Pioneered by Telsa [9] over a century ago, it is only until recently that the technology enjoys so much popularity attributed to the work of Kurs *et al*. [10], [11]. In [10], it has been shown that energy can be transferred between magnetically coupled coils in excess of 2 meters with efficiency of 40%. In [11], the prototype is further extended to power multiple devices. Within a few years, these findings soon become the impetus to drive the rapid growth and expansion of wireless energy in consumer electronics, health care, electrical vehicles, etc. For example, wireless charging pads (Powermat) offer the freedom to charge mobile devices without connecting charging cables whenever they are placed on the pad [12]. In health care, wireless charging of implanted batteries enjoys unique benefits by replacing traditional surgical operation to dispose old batteries. The technology also provides a convenient and powerful solution to the emerging Electrical Vehicle (EV) industry. With high efficiency to deliver hundreds of watts of energy, wireless charging systems can be launched at power stations, parking lots or even beneath road surface to recharge EV's battery packs without any physical contact [13].

For the next generation WSNs, wireless charging offers a novel, unique and reliable way to power sensor nodes and these networks are referred to as Wireless Rechargeable Sensor Networks (WRSNs). There have been some earlier works that utilize commercial products from Powercast [14] to charge sensor nodes wirelessly [15]–[18]. However, radiation-based wireless charging techniques (Powercast) have very low efficiency and can only transfer a small amount of energy, which makes it difficult to meet many demanding applications. In contrast, another wireless charging technique called magnetic resonant coupling proposed in [10] has high efficiency and supports transferring hundreds of watts of energy over a large air gap. To implement this technique in WRSNs, mobile vehicles equipped with resonant coils and high-density battery packs can approach nodes in

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Corresponding author email: yuanyuan.yang@stonybrook.edu
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very close proximity and deliver wireless energy to the nodes with high efficiency [19]–[25]. Hence, how to schedule a fleet of vehicles to meet dynamic energy demands from nodes such that no one depletes energy is a major research issue [24], [25]. In addition, practical constraints such as vehicle's recharge capacity, moving cost pose great challenges and further complicate the problem [25]. These problems are usually NP-hard in nature and fast algorithms with acceptable results are more desirable given the network dynamics [23]–[25]. Another research issue of paramount importance is to integrate wireless charging with typical sensing applications, e.g., data collection. Joint consideration of mobile data collection and wireless charging on a single vehicle is first studied in [21], [22]. Since mobile data gathering has known benefits to balance energy consumptions in the network, combining these two utilities not only saves manufacturing cost of the vehicles but also improves energy efficiency of the network.

Driven by the ongoing research in wireless charging and recent advance in battery technology, we also envision direction for the future trends in WRSN design. A limitation of the state-of-the-art WRSN design is network scalability. That is, the mobile vehicle needs to spend a considerable amount of time to recharge a single sensor node. If recharge time can be reduced and multiple nodes can be charged at the same time, network scalability can be significantly improved. To this end, we point out potential research issues based on the latest advancement in multi-hop wireless charging and ultra-fast battery charging technologies.

In this paper, we present an overview and outlook for WRSNs. In Section II, we classify wireless charging techniques according to their mechanisms, i.e., electromagnetic radiation and magnetic resonant coupling, and introduce their applications in WRSNs. In Section III, we identify open research issues and describe recent efforts to resolve these challenges followed by Section IV to envision future trends in this area. Finally, Section V concludes this paper.

II. Wireless Energy Transfer in Sensor Networks

In this section, we introduce two basic techniques of wireless energy transfer that have been utilized in WRSNs. We also briefly discuss previous works that have employed them in WRSNs.

A. *Electromagnetic Radiation*

Electromagnetic radiation has been utilized for wireless communication for more than a century. Recently, researchers have focused on capturing energy that resides in the ubiquitous electromagnetic waves to power small devices. A diagram of an electromagnetic radiation-based wireless charging system with one transmitter and two receivers are shown in Fig. 1. However, an inherent drawback of this method is due to the nature of ubiquitous wave propagation. The signal strength decreases dramatically with transmission distance. Thus only a small amount of energy carried by electromagnetic waves emitted from an antenna can be captured from the air, which can only support low-power devices such as sensor nodes.

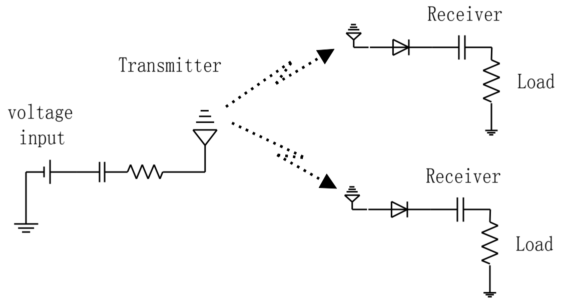


Fig. 1. Electromagnetic radiation-based wireless charging system with one transmitter and two receivers

There are several existing works on WRSNs based on products from Powercast [14] for wireless energy transfer, which operates at 850-950 MHz and charges low-power devices up to a distance of 3 meters. In [15], the impact of wireless charging on routing and deployment in current sensor networks is studied. In [16], [17], the problems of how to place/mobilize wireless chargers to sustain network operation and minimize recharge latency are investigated. In [19], an $O(k^2 k!)$ (where k is the number of nodes) algorithm is designed to schedule recharge activities such that network lifetime is maximized. Issues other than recharge scheduling are studied in [26], [27]. In [26], the safety issue of using radiation-based wireless charging is studied. A placement problem on how to place the chargers is studied such that no location has radiation exceeding a threshold. In [27], it is shown that traditional localization of nodes can be leveraged from the charging time of nodes. However, since Federal Communication Commission's (FCC) regulatory maximum Effective Isotropic Radiated Power (EIRP) is 4W [28] and omni-directional antenna emits energy that attenuates quickly over distance, this technique usually has very low efficiencies and only supports very low-power sensing applications such as simple temperature, humidity reading, monitoring, etc. Thus, in the rest of this paper, we mainly focus on wireless charging based on magnetic resonant coupling.

B. *Magnetic Resonant Coupling*

In contrast, magnetic resonant coupling can transfer energy at high efficiency over a large air gap as shown in [10]. It can be easily realized by magnetically coupled coils at the transmitting and receiving side as shown in Fig. 2. For WRSNs, vehicles equipped with high-density battery packs can be adopted as the energy transporters. While approaching a sensor node, the vehicle converts battery energy to alternating current and induces an oscillating magnetic field around the transmitter coil. Once the receiver coil on the sensor node tunes to resonate at the same frequency with the transmitter coil, an AC current is generated to the output circuit and regulated to recharge sensor's battery.

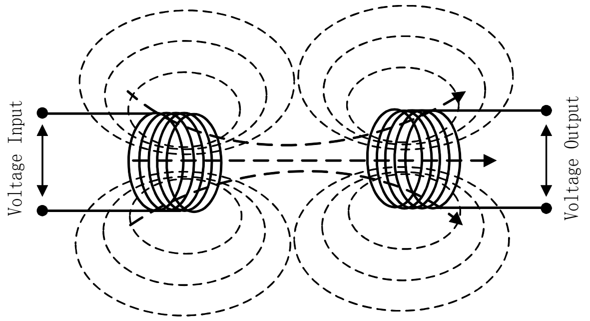


Fig. 2. Magnetic resonant coupling between a transmitting and receiving coil

Much effort has been devoted to address wireless charging in WRSNs using magnetic resonant coupling. In [19], an optimization problem to maximize the ratio between charging vehicle's idling and working time is studied. A Hamiltonian cycle through all the nodes is proved to be the shortest recharge path. In [21], [22], joint consideration of data collection and energy replenishment on a single vehicle is investigated. The vehicle first determines the nodes for recharge and plans the shortest route while guaranteeing a bounded tour length. During recharge, the vehicle gathers data from the neighborhood in multi-hops and uploads all collected data to the base station after a recharging cycle is completed. Since the dynamics of energy consumptions may cause inaccurate recharge decisions, in [23], a real-time energy gathering protocol is proposed. The protocol incorporates a hierarchical division of network field into smaller partitions to allow scalable and efficient message convergence whenever queried by the vehicle. The problem is formulated into an Orienteering Problem with a single vehicle. By taking reasonable approximations, the Orienteering Problem can be approximated by a Knapsack problem and dynamic programming solutions are available to solve the problem efficiently. To schedule multiple vehicles, an on-line algorithm that minimizes the weighted sum of vehicle's traveling time and node's residual lifetime in each step is proposed in [24]. Further, to be more practical, the vehicle's own recharge capacity and moving cost are brought into consideration in [25]. In sum, magnetic resonant coupling technique is ready to support many today's multimedia sensing applications with enormous data communications and sensing activities.

III. Wireless Rechargebale Sensor Networks

In this section, we describe the basic network architecture for WRSNs by introducing network components, principles and various issues that are undertaken by the research community. First, in subsection III-A, we describe the key network components. In subsection III-B, we introduce the basic principles from the theoretical aspect. In subsection III-C, we present a scalable communication protocol that is capable of querying energy information from designated regions in the network. In Section III-D, we discuss the critical issue of recharge scheduling followed by the discussion on how to integrate wireless charging with typical sensing applications in Section III-E.

A. Network Components

We first introduce the main components in WRSNs.

***SenCars**:* SenCars are multi-functional all-terrain vehicles. Equipped with high-density battery packs, SenCars could carry FPGA boards for fast computations, resonant coils for wireless charging and powerful antennas for communications. They periodically request nodes for energy information, select nodes for recharge and gather sensed data from the network.

Base Station: A base station serves for maintenance and network management purposes. SenCars can be commanded and programmed remotely by system administrators from the base station. When SenCar's own battery is low, it returns to the base station for battery replacement and uploads gathered data.

Areas: An area is a geographical organization of sensor nodes. Nodes within the same area share the same network address prefix to route messages. To be scalable, the network is hierarchically divided into different areas.

Head nodes: A head node is selected in each area to aggregate data messages from subordinate areas. When queried either by a SenCar or head node from the upper level, it queries data from subordinate sub-areas at the lower level, aggregates towards the upper level. Periodic rotation of head nodes is performed to avoid depleting their batteries.

Normal Nodes: A node not selected as a head node is a normal node. It performs basic sensing applications and responds to queries from the head in its area.

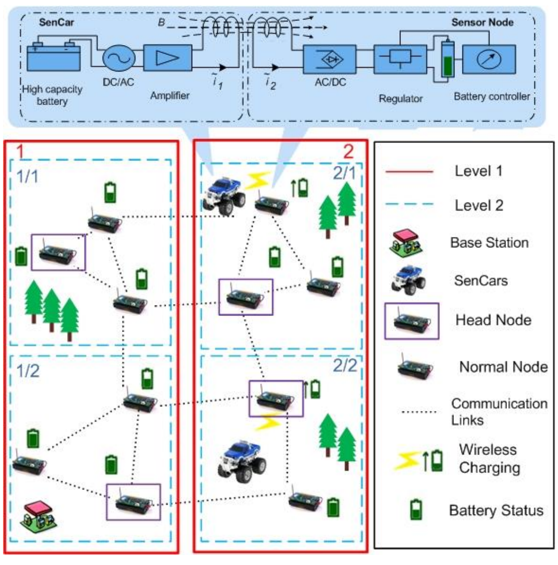


Fig. 3. Basic network components of a WRSN

Fig. 3 shows a WRSN with two levels. For clarity, the boundaries of the areas are divided based on geographical coordinates. In practice, the organizations of areas could be determined by various conditions such as energy consumption, connectivity and density, etc. Nodes in the same area are assigned the same network address prefix. For example, nodes in the top left area have the same prefix “1-1”. As an example, to identify the third node in that area, the address “1-1-3” can be used.

B. Principles to Maintain Perpetual Operation

To maintain perpetual operation of WRSNs, it was proposed in [25] that the energy neutral condition should hold for a long time period *T*,

$$\mathrm{E(T)} \leq \mathrm{R(T)} + \mathrm{E_0} \tag{1}$$

in which $\mathrm{E_0}$ is the initial energy of the network, and $\mathrm{E(T)}$ and $\mathrm{R(T)}$ are energy consumptions and replenished in time *T* respectively. Next, let us briefly describe how $\mathrm{E(T)}$ and $\mathrm{R(T)}$ can be estimated. $\mathrm{E(T)}$ can be calculated as the sum of energy consumptions on all the sensor nodes. As energy consumption is determined by communication patterns, how data is collected would have an impact on network energy consumptions. In general, there are two typical data gathering methods: static data gathering by base station or mobile data gathering by the SenCar. For static data gathering, sensors forward their messages towards the base station in multi-hops. Although it offers a simple approach to aggregate sensed data, it is subject to the infamous energy hole problem [29] that sensors near the base station are more prone to deplete their battery energy and cause network disruption. Mobile data gathering has known benefits to balance energy consumptions and mitigate the energy hole problem [30], [31]. Next, we briefly describe the method to calculate $\mathrm{E(T)}$ for static data gathering. After packet routing has been determined (e.g. using the Dijsktra’s shortest path algorithm [32]), a routing tree is formed rooted at the base station with sensor nodes as its leaves. Each node consumes energy for transmitting its own data packets and forwarding packets from its children nodes. Thus, from the number of its children nodes and their traffic rates, the total energy consumptions in the network can be obtained. For mobile data gathering, a similar method can be used. Since SenCars’ locations are constantly changing, they can be visualized by a number trees rooted at different sensor locations. Therefore, given the range of data gathering (e.g. m hops), we can obtain the average energy consumption of each node and based on this value, we can estimate average energy consumption from all the nodes in time T.

To calculate$\mathrm{R(T)}$, we need to know how long it takes a SenCar to fully replenish a sensor’s battery, which is usually governed by battery characteristics. Once the recharge time is known, it puts a limit of how many sensor nodes a SenCar can recharge in the time period T. Therefore, the collective recharge energy in T for a certain number of SenCars can be calculated. After $\mathrm{E(T)}$ and $\mathrm{R(T)}$ are calculated, we can see the feasibility of network plans given different settings such as field size, node number, traffic rate and number of SenCars, etc. After the network plan is settled, there are several interesting issues to solve next. First, how to gather real-time energy information in a scalable manner; Second, based on the energy information, how to schedule SenCars to recharge nodes such that no one depletes battery energy and the traveling cost of SenCars is minimized; How to approach this problem when practical constraints such as dynamic battery deadlines, SenCar’s recharge capacity and moving energy cost are considered; How to seamlessly integrate wireless charging with some typical sensing applications like data collection and target detection. In the following, we introduce the solutions to these issues.

After $\mathrm{E(T)}$ and $\mathrm{R(T)}$ are calculated, we can see the feasibility of network plans given different settings such as field size, node number, traffic rate and number of SenCars, etc. After the network plan is settled, there are several interesting issues to solve next. First, how to gather real-time energy information in a scalable manner; Second, based on the energy information, how to schedule SenCars to recharge nodes such that no one depletes battery energy and the traveling cost of the SenCars is minimized; How to approach this problem when practical constraints such as dynamic battery deadlines, SenCar’s recharge capacity and moving energy cost are considered; How to seamlessly integrate wireless charging with some typical sensing applications like data collection and target detection. In the following, we introduce the solutions to these issues.

C. Principles to Maintain Perpetual Operation

In this subsection, we present an overview of a real-time energy information gathering protocol proposed in [24]. The communication protocol allows the SenCars to query nodes for energy information on-demand in a scalable manner. Since the SenCars’ locations are constantly changing, a trivial way to reveal their locations is by flooding energy request messages in the network. However, this scheme would incur tremendous message overhead and is not scalable to network of large sizes. To this end, we hierarchically divide the network into different levels and each level consists of a number of areas. For each area, energy information is aggregated on head nodes.

During initialization, the head nodes are selected in a bottom-up fashion in the network by propagating head selection messages. To guarantee robustness, head nodes are selected with the maximum battery energy in their subordinate areas. Due to message aggregation and computation, head nodes usually consume energy much faster. When it is low on energy, it sends out a head notification message to delegate another node with maximum energy as the new head. During the head selection process, message routings to the head nodes on each level are established on each sensor node. Once a SenCar is idle, it initiates an energy information gathering process by sending out an energy request message to the head node on the top-level. Upon reception of a top-level energy request message, a normal node forwards this message towards the top-level head according to the routing entries. After the head node receive the energy request, it checks the requesting area in the message and sends out a new energy request message in respective sub-areas. The energy request repeats down the network until all the nodes in the bottom-level areas receive such request. After receiving a bottom-level energy request, nodes send out their updated energy information, lifetime and identification to the superior head nodes on the upper-level. To minimize message overhead, the superior head nodes checks whether a sensor node is below its recharge threshold, aggregates all the nodes that need recharge in a combined energy information message and sends it to its superior head nodes. The energy information uses the routing tables established on normal nodes to reach the head nodes. The energy information aggregates up through the network hierarchy until the SenCar receives the requested information. In case a node is on the verge to deplete its energy, instead of waiting until the next round of energy request, it preemptively sends out an emergency message to the head node on the top-level. This would avoid the lengthy propagation process between different levels for emergencies. At the same time, the head node maintains an emergent node list. Once a SenCar finishes recharging a node, it polls the top-level head node to see whether there is any emergency. If yes, it switches to the emergency recharging mode and proceeds immediately to resolve their energy request. The emergency recharge scheduling algorithm will be discussed in the next subsection.

Finally, let us explain the mechanism of this protocol by an example. Based on Fig. 3, let us say the SenCar is interested in charging nodes in area “1/2” with their energy below the recharge threshold. Then the SenCar sends out a query on the top level (“1”). Upon receiving this query, based on the routing table, nodes forward this query to the head node on the top level. The head node examines the destination address of the query and forwards the message to the corresponding sub-area. This process is repeated until the destination area “1/2” is reached. Then nodes in that area with energy below the threshold respond to the query with their energy information to the head node. The energy information messages are aggregated at the head node and relayed until the SenCar is reached. In this way, although the SenCars are constantly moving during the operation, the routing information is accurately updated on intermediate nodes by recording which direction the query messages are coming from.

For the protocol to be robust against any link failure, the query messages should be able to bypass any nonfunctional nodes on the routing path. That is, whenever a sent message receives no acknowledge from a node’s neighbor or the node detects a sudden drop of radio activities from a neighbor, it updates its routing table by selecting the next available neighboring node for forwarding messages. In the meanwhile, the node will also need to pinpoint the location of its nonfunctional neighbor and report to the SenCar for recharge. This process adds robustness guarantee to the work of [24] in case any node depletes its battery in the process of energy information gathering.

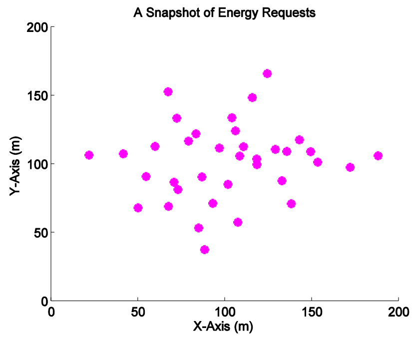
D. Recharge Scheduling

After energy information has been collected, a global energy map can be visually analyzed by SenCars. Then the next important objective is to schedule a number of SenCars to keep all the nodes alive and minimize the traveling distance of SenCars. This is referred to as perpetual operation of the network and one of the primary goals in the designs of WRSNs. Seeking an optimal solution to schedule a fleet of SenCars for recharge is usually an NP-hard problem whereas traditional efforts of standard optimization techniques are not cost effective given limited computation resources on the SenCar. Thus, heuristic algorithms are usually proposed in practice to achieve a reasonable balance between optimality and computation complexity.

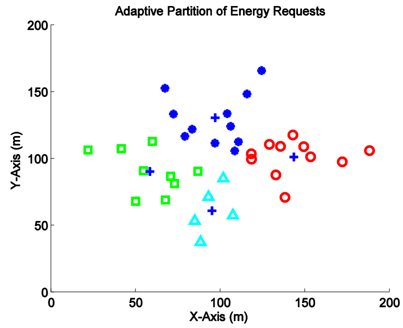
In [23], the problem to schedule a SenCar for emergency recharge is studied. In order to resolve as many emergent nodes as possible before the next emergency occurs, the SenCar needs to maximize the energy replenished back into the network within a limited time threshold. The problem is formulated into an Orienteering Problem. In the Orienteering Problem, a set of control points associated with scores are visited by competitors before a time expiration, and the competitor collecting the highest score wins the game. The problem aims to find the highest score in limited time durations. The problem is NP-hard. However, it has been shown in [23] by utilizing the fact that traveling time is negligible compared to recharge time since traveling time is usually 1-5 mins whereas recharge time requires more than 60 mins. Therefore, the traveling time of SenCar can be ignored and the Orienteering Problem can be closely approximated by a Knapsack problem. Then we can apply classic dynamic programming method to solve the problem in polynomial time.

In [24], a more general case with multiple SenCars and dynamic battery deadlines is considered. Based on the energy information, an on-line algorithm that aims to select the next node with the minimum weighted sum of traveling time and node lifetime is proposed. The weighted sum method is used to balance conflicting factors in the problem. That is, on one hand, to minimize SenCars’ traveling cost, it is desired to move to the nearest node requesting recharge, which may be far away from SenCar’s location. On the other hand, to meet node’s battery deadline, SenCars should prioritize nodes with shorter estimated lifetime. The algorithm runs in polynomial time with acceptable performance compared to the optimal case.

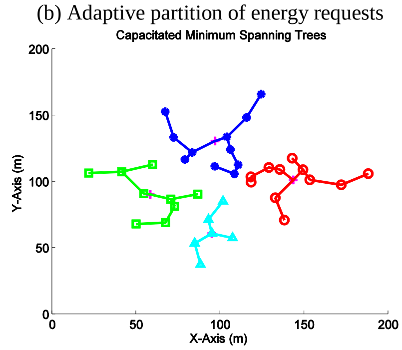
Additionally, bringing more practical aspects would be beneficial for real applications and design the network but it certainly complicates the algorithm designs. For example, if the SenCar's own battery capacity is not considered in algorithm design, it may be stranded during operation and unable to return to the base station for battery replacement. In addition, the moving cost of SenCar should be also considered to avoid long distance movements. In [25], a set of practical constraints of SenCar's own recharge capacity, moving cost and nodes' battery deadlines are considered. With the needs of better route plans and desires to meet sensors' battery deadlines, we need to coordinate the activities among the SenCars. To tackle these challenges, a 3-step adaptive algorithm is proposed in [25]. We illustrate operation of the algorithm through an example in Fig. 4. Fig. 4(a) gives a snapshot of energy request during the operation. To keep the movement of SenCars in their confined scopes, the network is partitioned adaptively according to the recharge requests (Fig. 4(b)). The well-known K-means algorithm can be used [33]. The K-means algorithm aims to minimize the total square of sum of distance to a set of centroid positions. The centroid position is chosen as the starting position of each SenCar. After each SenCar has been assigned a working region, they compute Capacitated Minimum Spanning Trees (CMST) independently as shown in Fig. 4(c). The CMST is a minimum spanning trees with capacity threshold so it can naturally capture the recharging capacity of the SenCar and indicate from which subset of nodes the SenCar should choose to minimize the traveling cost. Finding the CMST first can also ensure the nodes on the same tree are placed in the same recharge route later. After the CMSTs are formed, the SenCar needs to further capture the sensors' battery deadlines. To improve the previous weighted-sum algorithm from [24], the SenCar categorizes nodes according to their lifetime. If a node's lifetime is enough to last for the total recharging time of the entire recharge sequence, it can be placed at any arbitrary position in the sequence. We denote these nodes as "non-prioritized nodes". On the other hand, if a node's lifetime is not enough, it needs to be inserted at advantageous locations in the sequence and each insertion should retain the battery deadlines of all the nodes in the recharge sequence. We denote these nodes as "prioritized" nodes. The algorithm first computes the recharging route of the non-prioritized nodes using a classic Traveling Salesmen Problem algorithm, e.g. the nearest neighbor or Christofides algorithm [32]. Then it inserts prioritized nodes into the recharge sequence iteratively while maintaining the time feasibility and minimizing the moving cost of the SenCar for each insertion. The final recharge routes are shown in Fig. 4(d). The aforementioned works have provided initial attempts to solve complicated recharge scheduling problems. For future works on this topic, a more general problem that encompasses stochastic energy demands should be considered. In [34], theoretical results for on-demand wireless charging have been studied. A queuing model has been established and important characteristics have been proposed such as throughput and charging latency. Based on the analysis in [34], stochastic recharge policies can be developed in future.



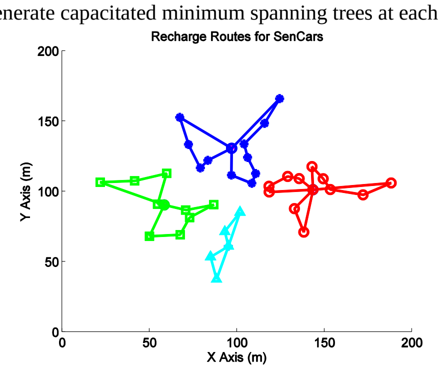
(a) A snapshot of energy requests



(b) Adaptive partition of energy requests



(c) Generate capacitated minimum spanning trees at each SenCar



(d) Improve recharge routes to capture sensor's battery deadlines

Fig. 4. An example of recharge scheduling algorithm in [26]

E. Integrate with Typical Sensing Applications

How to efficiently integrate wireless charging with typical sensing applications is also an interesting but difficult problem in general. It involves multiple variables to optimize from spatial and temporal domains. The intertwined relationships between these variables greatly harden the analysis. Next, we give an overview of research efforts that jointly consider wireless charging with data collection and target detection. We also point out limitations in the current studies for improvements in future.

1) ***Integrate with data collection***: The works of [21], [22] have given a first try to combine data collection and wireless charging on a vehicle. In [21], a two-step approach is adopted to maximize the utility of the network. Sensors periodically report their energy to the base station and the nodes are sorted in an ascending order according to their battery energy. In the first step, the algorithm uses binary search to find the maximum number of sensors with the least amount of energy, and meanwhile by visiting these sensors, the tour length of the SenCar is no more than a threshold value which implies bounded data latency. After the candidate recharging nodes are selected, the SenCar migrates through these nodes. While at each sensor location, it informs nodes in the neighborhood of its presence and collects data from the neighborhood in multi-hop fashion. In the second step, a non-convex communication optimization problem is formulated to maximize overall data gathering utility based on where the SenCar stops to recharge nodes. The problem is converted into a convex one by introducing auxiliary variables and partitioned into several sub-problems using Lagrangian dual decomposition method. The sensors calculate their optimal data and flow rates on all the links in a distributed fashion. The SenCar also allocates the optimal recharging time (stopping time) at each sensor location [22].

These works mark an encouraging first step to integrate wireless charging with typical applications such as mobile data collection. However, the problem is more difficult than it appears after some analysis. That is, single-objective formulation of the problem may not consider all aspects of the network. On one hand, the SenCar needs to recharge sensor nodes according to their current energy levels. The objective here is to keep all the nodes functional as well as minimize the traveling cost of the SenCar. On the other hand, mobile data collection aims to collect as much data as possible. The SenCar should be driven to the areas with more data. The desire to maximize replenished energy into the network may not always meet the goals to optimize data gathering. The neighborhood with less energy cannot sustain a large amount of data gathering. Thus, we can see potential conflicts between achieving different goals by placing data gathering and wireless charging on the same vehicle. The analysis in [21], [22] may not be sufficient based on a single-objective formulation. A multi-objective formulation would better characterize these conflicting goals. It would have a significant impact on algorithm designs. In the previous works, the SenCar stops only for recharging and simultaneously gathers data. In a multi-objective formulation, the SenCar may stop for both recharging and data gathering at different locations. In this way, network performance can be further improved. In addition, another potential challenge comes from the interdependent relations between recharge and energy consumption. In [21], [22], although nodes at SenCar's stopping locations are recharged, their neighboring nodes have consumed energy for relaying data packets. These nodes may also request for recharge whereas the algorithm only considers these nodes in the next round because decision is made prior to a recharge tour. These pre-determined recharging nodes may not accurately reflect the network energy status during the actual data collection. To successfully solve this complicated problem, an energy consumption model based on mobile data gathering should be studied to analyze the impact of energy consumptions on recharge decisions. These problems would be important research issues to be solved in future works under this topic.

2) ***Integrate with target detection***: Another ubiquitous sensing application is target detection and tracking. In traditional WSNs, sensor nodes cooperate to sense targets/events that usually appear as random processes. Due to limited battery energy, activations of communication and sensing activities are coordinated to extend network lifetime by taking advantage of the duplicated covering areas (redundancies) [35], [36]. In other words, when a target is being covered by multiple sensors, they can organize into a group and form activation/sleep schedules to achieve target coverage and energy saving at the same time. For WRSNs, how to jointly design recharge schedules on the SenCars with sensor activation is an interesting problem. The optimal activation policy and coordination scheme should not only depend on the energy consumptions on sensor nodes, but also the cost on SenCars. A policy that schedules nodes to activate in a rotational manner so that target detection quality is satisfied and the SenCar can make one move to recharge a bunch of nodes in close proximity could be a good direction to start with [37]. In Fig. 5, we give an example to show joint target detection and wireless charging design can save system cost. The nodes monitoring the same target node can be organized into a temporary cluster. If sensor's duty cycles can be adjusted such that nodes can request recharge almost at the same time, the SenCar can recharge all the sensors in a cluster in one shot. This joint design helps SenCars avoid coming to the same cluster back and forth and save a great amount of moving cost on them. Therefore, we can see that the integration of wireless charging with typical sensing applications requires much deeper understanding and analysis between the recharge scheduling and classic problems in WSNs research. A preferable way while designing algorithms is to think these problems as different parts in a system and the operation of each depends on the feedbacks from others. A global view of these related parts would open more future venues

for this problem.

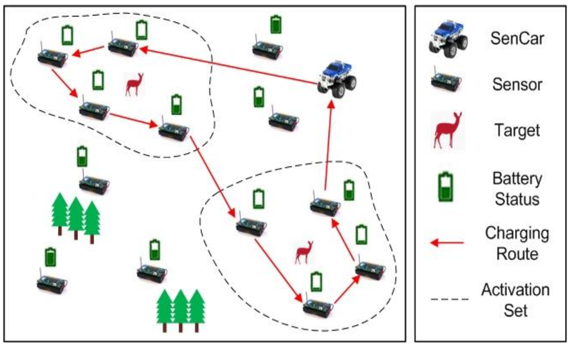


Fig. 5. Joint target detection and wireless charging

IV. FUTURE TRENDS

In this section, we present an outlook of the future trends in WRSNs. So far, many research topics are still open and require extensive and widespread efforts. In the following we describe several promising technologies and their possible impacts on WRSNs. One of the main technical barriers currently is network scalability. Given limited charging range, the SenCar needs to approach nodes in close proximity and recharges them one by one. The recharge time which depends on the battery used exacerbates network scalability because recharging traditional Nickel Metal Hydride (NiMH) batteries usually lasts for several hours and charging a couple of nodes sums up to tens of hours. The limited charging range and slow battery charging time are the main technical barriers to network scalability. In addition, how to recharge the SenCar and what the power source is, are also important questions that should not be ignored in practice. Eco-friendly ambient energy sources can meet the anticipation to build a green network. How to combine the advantages from energy harvesting and wireless charging to design a self-sustainable, autonomous sensor network could be a future direction. Based on recent fundamental results in physics and power electronics, we map the trends for future research in WRSNs.

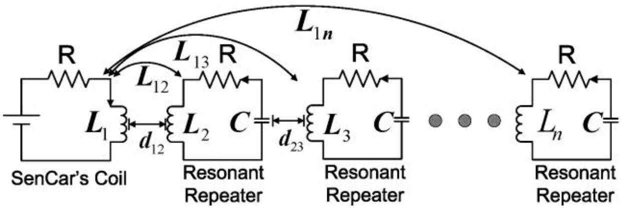


Fig. 6. A schematic overview of multi-hop wireless energy transfer

A. *Extend Charging Range*

With the development of short-range wireless energy transfer reaching a mature stage, research of the mid-range implementation is gaining momentum these years. Since coupling factor between resonant coils decreases exponentially with transmission distance, mid-range energy transfer over distance that exceeds the dimension of coils has been an open challenge for decades. In theory, wireless charging efficiency is governed by mutual inductance between transmitting and receiving coils [39],

$$\mathrm{L_{ij}} = \mathrm{k_{ij}}(\mathrm{n_t L_s})^2 = \frac{\mathrm{r_s^3}}{2\mathrm{d_{ij}^3}}(\mathrm{n_t L_s})^2 \tag{2}$$

in which $\mathrm{L_{ij}}$ is the mutual inductance between coils *i* and *j*, $\mathrm{n_t}$ is the number of turns of the coil, $\mathrm{k_{ij}}$ is the magnetic coupling coefficient between *i* and *j* ($0 \le \mathrm{k_{ij}} \le 1$), $\mathrm{L_s}$ is the coil's self-inductance, $\mathrm{r_s}$ is the radius of the coil. From Eq. (2), we can see the mutual inductance decays as an inverse cube of charging distance. Eq. (2) only shows the decay in one-hop wireless charging of very limited distance. The latest research in power electronics found that resonant repeaters can increase the end-to-end mutual inductance in multi-hop wireless charging thereby extending the charging range [38]–[40]. Fig. 6 gives a schematic view of relaying energy by resonant repeaters. The repeaters can be built from copper coils at very low cost. In [38]–[40], it has been shown that by adding resonant repeaters between transmitting and receiving coils, a significant improvement in wireless charging efficiency can be achieved. In particular, a wireless charging system in [39] with 4 resonant repeaters is able to distribute 15 mW in a distance of 2 meters to 6 loads. In [40], resonant repeaters are organized into a domino form. The results have demonstrated the system can support up to 70% efficiency after 6 energy relay hops. With this advance, the current one-hop wireless charging technique can be upgraded to support multi-hop energy delivery. A resonant repeater circuitry can be cheaply manufactured and added into the current designs. In this way, when the SenCar stops at a sensor location, the charging energy can be relayed in multi-hops to replenish nodes' batteries in the neighborhood. In [41], Multi-hop wireless charging is envisioned in which a number of SenCars stop at designated locations to recharge nodes in the neighborhood such that energy loss in multi-hop relay and their moving cost are minimized.

To successfully implement such design, a couple of issues need to be addressed in future. First, the installation of coils should be designed to form an array to handle non-coaxial reductions of coupling during energy relay. This requires efforts from hardware designs to allow misalignments between sensors' coils. Second, the repeater circuitry on sensor nodes also needs to ensure the overall energy efficiency. For example, when receptive energy efficiency is very low, it needs to "stop" relaying energy to other sensor nodes to guarantee overall energy efficiency. Finally, the existing recharge scheduling policies should be extended to support multi-hop wireless charging. Based on the distribution of sensors, where the SenCars should stop to recharge nodes in the neighborhood is an interesting problem. A model to characterize charging efficiency and optimization framework to schedule multiple SenCars need to be developed. By addressing these fundamental issues, we will be able to implement the latest advance of multi-hop wireless charging in WRSN and improve network scalability significantly.

B. Ultra-Fast Battery Charging

Another limitation of the current design comes from the slow recharge process of traditional NiMH batteries. Although the wireless charging power can be high, charging rate is dictated by battery characteristics. Typical sensor nodes equipped with NiMH battery requires at least an hour of recharge time. For large network sizes, a sequence with several tens of nodes would last for days. Driven by the surging demand from mobile devices, a promising technology that is ready to hit the market is ultrafast battery charging. Previous explorations have focused on new ways to use suitable materials such as $LiFePO_4$ in order to achieve high charging rates. In [42], a new way that allows the $Li - ion^+$ to migrate through electrodes can successfully recharge a standard battery cell in 5-6 minutes. Recently, a novel bio-organic ultra-fast charging technology developed by Israeli researchers can fully recharge an Apple iPhone in 30 seconds [43]. The new technology has changed the traditional battery design to permit rapid absorption of energy through synthesized molecules. Although this technology is still at prototyping stage, it is expected to be available in the next few years with relative low cost given the increasingly ubiquitous energy demands from mobile devices. If a sensor's battery can be fully replenished in only a few seconds, a SenCar can finish charging tens of nodes in just a couple of minutes rather than in days. This revolutionary breakthrough would have tremendous impacts on the current WRSNs. Obviously, the network scalability can be greatly improved. A SenCar can take care of more nodes without worrying about battery depletion due to extended recharge latency. In addition, the timing cost currently dominated by recharge time with traditional NiMH battery would no longer hold. In contrast, moving time of the SenCar to destinations would become comparable or even larger than the recharge time. This would result some significant changes in the algorithm while making recharge decisions. In the current algorithm designs, the SenCar always needs to travel in long distance for recharge in order to maintain perpetual operation on sensor nodes. With ultra-fast charging, the SenCar can maximize its recharge efficiency by adding more nodes along the recharge routes since the aggregated recharge time will have little impact on meeting battery deadlines. As a result, we can see ultrafast charging can improve energy efficiency in WRSN from different aspects.

C. Designing Hybrid WRSN

Although wireless power provides a reliable energy source for sensor nodes, it is subject to a few physical limitations such as charging distance and human safe power density. Environmental energy harvesting techniques provide safe, eco-friendly, renewable sources and much higher power density than wireless charging. However, as mentioned earlier, the main challenges are the uncertainty and variation from the power source. For example, in a solar-powered WSN, nodes fall into shades have to reduce their workload to conserve energy. Combining environmental energy harvesting and wireless charging to form a hybrid network can mitigate the drawbacks from both technologies. We can launch energy harvesting devices on sensor nodes at selected locations so these energy-rich nodes can form a virtual backbone to relay data packets. Optimization of where to deploy these nodes with ambient energy sources is a location problem [44]. The algorithm should consider multiple factors from space and time. First, a model to estimate time-varying, spatially dependent energy harvesting rates should be established. For example, in solar-harvesting networks, these nodes should be placed at advantageous locations under sunlight without any obstructions around. Besides, the placement patterns need to balance energy consumptions on wireless-powered nodes such that no sensor is overloaded. These nodes form a connected backbone to the base station for forwarding sensed data. Based on the location of these nodes, the second question is how sensors would adjust their data rates and intermediate link flow routings. For perpetual operation, the energy expenditure (data transmission and sensing) on both solar and wireless-powered nodes should be less than or equal to the energy income (energy harvesting rates). Finally, recharge routes for the SenCar can take advantage of these solar-powered nodes. They can be served as data aggregation points and the starting locations of recharge tours. During recharge, the SenCar can collect packets simultaneously from the neighborhood in multi-hops. Once the SenCar returns to the data aggregation point, it transmits all the collected data through the backbone towards the base station. In this way, the SenCar does not need to move back to the base station for data delivery and reductions of both packet latency and SenCar's moving cost can be achieved.

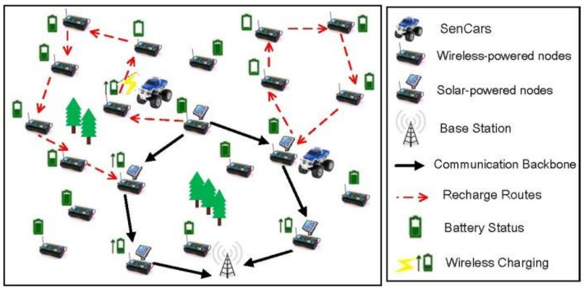


Fig. 7. A futuristic hybrid WRSN consists of solar and wireless-powered sensors

In addition, a hybrid WRSN also suggests implement energy harvesting devices on the SenCar. Since the SenCar is much larger than sensor nodes, deploying solar panel or wind turbine on it should be more effective to capture large amount of energy. To make sure harvested energy is enough to sustain network operation, the moving routes of the SenCar should be also energy-aware. Important questions such as when and where the SenCar should stop for recharging sensor nodes and capturing ambient energy along the route should be also explored. Fig. 7 gives a pictorial envision of a hybrid WRSN.

V. Conclusion

This paper aims to provide an up-to-date review on the current state-of-the-art in WRSNs. We have explored the most recent studies that address the critical issues in WRSNs and identified the open challenges that need to be tackled. These issues include scalable real-time energy information gathering, optimal recharge scheduling and integration of wireless charging with typical sensing applications. Then we pointed out possible future research directions based on the most recent discoveries and results from physics and power electronics. These are: 1) to improve network scalability, wireless charging range extension by resonant repeaters and ultra-fast battery technology would be beneficial; 2) a hybrid and green WRSN that combines renewable environmental energy sources with wireless energy to power nodes and the SenCar can provide an autonomous, eco-friendly and perpetual sensor network in future.

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Yuanyuan Yang received the BEng and MS degrees in computer science and engineering from Tsinghua University, Beijing, China, and the MSE and PhD degrees in computer science from Johns Hopkins University, Baltimore, Maryland. She is a professor of computer engineering and computer science at Stony Brook University, New York, and the director of Communications and Devices Division at New York State Center of Excellence in Wireless and Information Technology (CEWIT). Her research interests include wireless networks, data center networks, optical networks and high-speed networks. She has published more than 270 papers in major journals and refereed conference proceedings and holds seven US patents in these areas. She is currently the Associate Editor-in-Chief for the IEEE Transactions on Computers and an Associate Editor for the Journal of Parallel and Distributed Computing. She has served as an Associate Editor for the IEEE Transactions on Computers and IEEE Transactions on Parallel and Distributed Systems. She has served as a general chair, program chair, or vice chair for several major conferences and a program committee member for numerous conferences. She is an IEEE Fellow.

Cong Wang received the BEng degree in Information Engineering from the Chinese University of Hong Kong and M.S. degree in Electrical Engineering from Columbia University, New York. He is currently working towards the PhD degree at the Department of Electrical and Computer Engineering, Stony Brook University, New York. His research interests include wireless sensor networks, performance evaluation of network protocols and algorithms.

Ji Li received the B.S. degree in Electrical Engineering from Harbin Engineering University, Harbin, China, and the M.S. degree in Electrical Engineering from Zhejiang University, Hangzhou, China. He is currently a PhD student in the Department of Electrical and Computer Engineering, Stony Brook University, Stony Brook, New York. His research interests include wireless sensor networks and embedded systems.