

Hybrid Micro-Energy Harvesting Model using WSN for Self-Sustainable Wireless Mobile Charging Application

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Abstract

The self-sustainable Wireless Sensor Networks (WSNs) face a major challenge in terms of energy efficiency as they have to operate without replacement of batteries. The benefits of renewable and green energy are taken into consideration for sensing and charging the battery in recent literatures using Energy Harvesting (EH) techniques. The sensors are provided with a reliable energy source through Wireless Charging (WC) techniques. Several challenges in WSN are addressed by combining these technologies. However, it is essential to consider the deployment cost in these systems. This paper presents a self-sustainable energy efficient WSN based model for Mobile Charger (MC) and Energy Harvesting Base Station (EHBS) while considering the cost of deployment. This system can also be used for low-cost microelectronic devices and low-cost Micro-Energy Harvesting (MEH) system-based applications. While considering the deployment cost, the network lifetime is maximized and an extensive comparison of simulation with various existing models is presented to emphasize the validity of the proposed model.

Keywords: Wireless Charging, Energy Harvesting, Energy-Efficiency, Wireless Sensor Networks, Internet of Things, Mobile Charger, Micro-Energy Harvesting

1. Introduction

Precision agriculture, environmental data monitoring and several other consumer and industrial applications make use of Wireless Sensor Networks (WSNs) in an extensive manner



over the recent decades [1]. The smart, cheap and small sensors and their availability is a major contributor towards the vast application domain in WSN. For this reason, several researchers have turned their attention towards exploiting this technology for good. Several factors also contribute to certain weaknesses in WSN. Despite the limited energy provided to the sensors, the system ensures appropriate Quality of Service (QoS) while enabling the network to perform in a self-sufficient manner [2]. MAC/routing protocols, adaptive control, duty cycling, and low-cost communication are some of the commonly used energy conservation schemes used in the WSN research to enhance the energy efficiency. Energy provisioning issues are not addressed despite enhancing the energy efficiency of the overall system. In large networks, the sensors are not feasible due to the energy depletion leading to the need for battery replacement [3]. Electromagnetic radiation, thermal, vibration, solar and wind energy may be used for acquiring energy from energy harvesters. This energy can be optimized to match the requirement of the sensors. During rainy or cloudy days, solar energy harvesting may be affected. Such constant interruption in power supply may be observed in the dynamic ambient energy sources [4, 5]. Solar-wind systems and other combinations of multiple energy sources enable enhancing the robustness of the system. However, when none of these energy sources are available, an energy shortage may occur in extreme weather conditions.

A reliable energy source is provided as a backup to the renewable energy sources with the help of wireless charging architecture [6, 7]. For effective charging, a proximity sensor-based approach is employed in mobile chargers (MC) due to their limited charging range. Various application and system level optimization and network layers are analyzed to estimate the WSN energy efficiency [8]. The fundamental energy supply issue needs to be addressed despite the success of all other mechanisms. Compact and low-cost wind turbines and solar panels are developed by researchers for energy harvesting. For wirelessly charging the sensors, MCs are also utilized. Each sensor has to be visited individually by the MCs making the systems barely scalable [9]. Continuous reporting, coverage and sensing required by the large-scale WSNs are provided with self-sustainability through a combination of wireless charging and multi-source energy harvesting. In ambient energy, the inherent dynamics is a major

challenge. The spatial temporal factors cause rapid fluctuations with the micro-climate variation in both wind and solar energy [10, 11]. The harvested energy is affected by humidity, temperature, building obstructions, foliage shades, sunlight angle, cloud movements and so on. For days, wind can stop completely during the humid and hot seasons. Solar irradiance is limited during the rainy days.

Communication, data processing and sensing must be planned accordingly while considering the temporal and spatial weather characteristics to achieve a cognizant system [12]. Robustness is not guaranteed by the energy-harvesting sensors due to the following reasons-during extreme weather conditions, the energy sources may all be unavailable [13]. Network disruption may be faced due to nonuniform distribution of energy, which can be overcome with wireless charging as a backup energy source to enable the sensors for sensing and transmitting data in an uninterrupted manner. The energy at the MC must be replenished automatically to make the system self-sustainable and fully automatic. Connecting the MC with the power grid and base station is proposed in most of the existing literature [14]. During pollution and wildlife monitoring and other similar ad-hoc applications, the unavailability of such infrastructure can be a hindrance. Energy Harvesting Base Stations (EHBS) with hybrid micro-energy harvesting model is proposed in this paper to store sufficient energy for uninterrupted functioning of the network. The EHBS battery is recharged when energy is depleted at the MC thereby relying on its own energy rather than on the power grid.

2. Literature Review

The network performance can be enhanced largely by reducing the energy consumption of the system. With the evolution of smart technology, the microelectronics industry has been gaining considerable attention [15]. Electrical energy is controlled, transformed and used in this technology. Lighting equipment, drive technologies, industrial process based power supplies and so on are some of the major applications of the microelectronic devices. The popularity of wireless system based applications has increased enormously over the recent

days. Ambient resources are powered by micro-energy harvesting (MEH) systems that help generate their own power when self-sustained or battery powered systems are considered [16, 17]. With the development of smart sensing technology, cropping, weather and several other applications make use of numerous wireless sensing devices that work in an uninterrupted manner for gathering and providing information [18]. On an everyday basis, the global intelligence trend of WSNs is increasing largely. After some time of usage, the batteries used in these numerous wireless sensors need to be powered. It will be a great challenge to power these trillions of wireless sensors, especially considering their continuous increase in number over time [19].

Along with designing better batteries, high efficiency and low cost parameters are also considered for the microelectronic and sensor devices [20]. In electronic devices, reliability, improvement, gap reduction and management are the main parameters of energy storage systems (ESS). Environmentally friendly, low cost, long life and maturity requirements of the ideal EES are not fulfilled by the commercially available systems that are currently available [21]. Energy management applications make use of batteries, cells and supercapacitors. Micro lead-acid and lithium-ion batteries are some of the advanced batteries that are currently available. While supercapacitors and nickel-cadmium batteries are developed, renewable energy storage batteries are still being researched upon. The cycle efficiency of supercapacitors is 60% while that of the renewable energy storage batteries are much higher. Low efficiency is observed by solar, chemical and thermal cells due to their large losses. Supercapacitors decide the cyclic life of the electrical system [22].

The benefits of long life cycles are enjoyed by the advanced thermal energy storage systems and automatic load transfer switches in mechanical and thermal EES. The poisonous portion, magnetic field and combustion makes the switch-mode power supplies and batteries not so eco-friendly. The supercapacitor and battery performance is affected by temperature and other environmental conditions [23]. At high temperature, the electrolyte in the battery starts boiling while it freezes at freezing point. This may lead to emission of carbon dioxide and other

chemical reactions at the ESS that affect the environment and cause harm to humans [24]. However, along with supercapacitors, the low voltage solar fuel cells are more eco-friendly.

3. Proposed Scheme

The energy and task demand is addressed by identifying appropriate sensors to formulate the solution. The MC moving cost is minimized potentially by placing the EHBS at strategic locations based on the deployment patterns and density of the sensors. The sensor charging activity is scheduled by the MC based on the EHBS locations and it then returns to refill the battery at the EHBS. The network plans and its fixed cost is initially reduced [25]. Further, the energy efficiency is enhanced and the operating cost is reduced. Later, the network operation without any disruption is ensured. This helps in optimizing the overall network cost and system design. A comprehensive cross-layer optimization model is considered for achieving these goals. The system design and solution space is complicated by the interdependence between the objectives. The sensor types and their density affect the EHBS deployment which can be addressed by solving the Sensor Composition Problem (SCP). The problem will be unsolvable if these factors are not considered individually. Hence, the SCP is addressed and then a three-tier algorithm is followed in a systematic manner to enable micro-energy harvesting in WSN for self-sustainable wireless mobile charging.

The network flow model is integrated with sensor composition problem in order to maintain the energy balance while finding the optimal sensor composition. This enables meeting the sink demands enabling feasible flows while ensuring least cost at the sensor nodes [26]. This model is represented in Figure 1. Here, the energy income is represented by the source and task based energy consumption is represented by the sink. The source is connected directly to the tasks and the sink via nodes as represented in the figure. The major components of the EHBS device are the solar and wind harvesting device as well as a large capacity battery. Different types of energy can be simultaneously harvested and stored in the battery. During

initial network planning, the estimated network energy required for consumption must be met by the EHBS total harvested energy in order to accomplish self-sustainability.

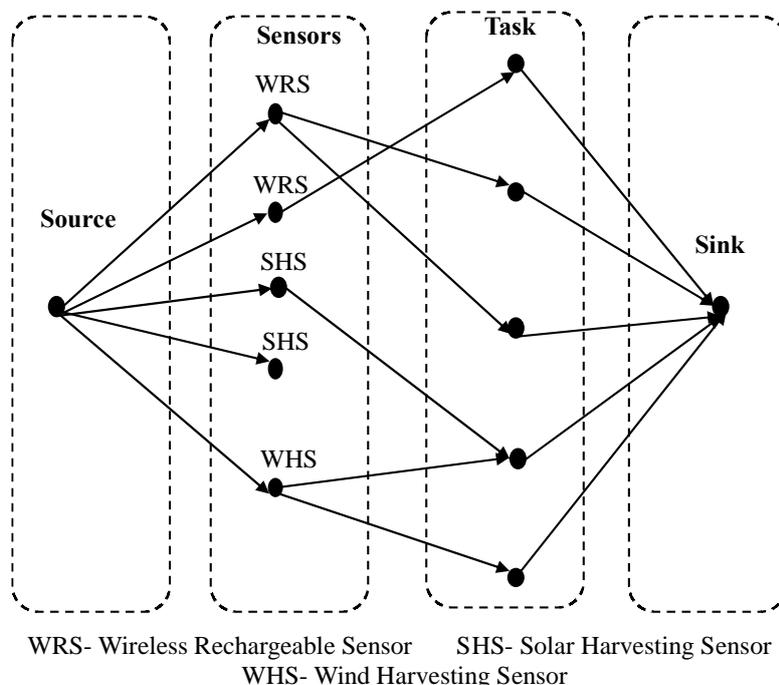


Figure 1. Network flow model to address the Sensor Composition Problem

The system is a hybrid network as it combines the conventional energy source along with the renewable module. Sufficient energy must be generated by the harvesting device. Energy is transmitted to the MC through a wireless charging interface by the EHBS. The nearest EHBS is visited by the MC for recharging when it depletes its own energy. In the three-tire algorithm, initially, the EHBS is deployed by dividing the field into regions of similar sizes. The Heuristic Field Division approach is followed for this purpose. Since EHBS have similar output power, deploying them to regions of similar size can minimize the variance of energy between different regions. This way, the network can avoid coverage holes due to energy depletion from the entire region. One EHBS is deployed for each region with the best coverage. In this subsection, the method to divide the field is studied.

Tire Algorithm

Step 1: Heuristic Field Division

Input: The field, number of regions, precision index

Output: Regions dividing the field

Step 2: Earliest Finishing First

Input: An empty set, a number of charging requests distributed in grids

Output: Energy replenishment and charging sequence for MC

Step 3: Shortest Interval First

Input: An empty set, a number of charging requests distributed in grids

Output: Energy replenishment and charging sequence for MC

Unless the maximum flow problem P is a nondeterministic polynomial, it is impossible to achieve an optimal solution in polynomial time due to the NP-hardness of the Reserved Group Interval Scheduling Problem (R-GISP) [27]. The R-GIPS considers the groups of intervals and looks for maximum sized non-overlapping representative sets. When compared to a given constant, the sum of the lengths of all intervals in the set is ensured to be smaller. The Earliest Finishing First algorithm is used in this context for removing all intersecting charging tasks and iterating the process until no tasks are left. The shortest interval first approximation algorithm is finally used as the duration of tasks is not considered here unlike the earliest finishing first algorithm. This helps in achieving a performance guarantee based on the ratio between the result and the optimal solution. The algorithm selects a task with shortest duration and removes it from intersecting with the specific task from the task set.

4. Performance Analysis

MATLAB based discrete-event simulator is used for the analysis of the proposed self-sustained framework and evaluation of its performance. Further, single energy source based

conventional models are compared with the proposed model. NREL and SOLARGIS are used for obtaining the data trace of wind power and solar radiation respectively for the purpose of simulation. A simulation time of 60 days is considered along with a 200 m long sensing field. The working sensors with 15-meter sensing range have an average energy consumption rate of 12 J/min for 1 hour equally slotted time. In order to charge the wireless rechargeable sensors from empty to full, a 3.7V, 1200mAH Li-Ion battery is used for a time period of 30 mins. The 2150mAh batteries of wind and solar powered sensors have a working voltage of 3.7V. The wireless rechargeable sensor manufacturing cost is much lesser compared to that of the wind powered and solar-powered sensors. 1.5Wh and 2Wh sensors that are wind-powered and solar-powered respectively are used for harvesting the maximum energy. For EHBS, the maximum energy that can be harvested ranges up to 2kWh. The energy consumption rate and speed of the MC is found to be 5J/m and 10 m/min respectively. The recharge request is sent when less than 20% of the threshold value is reached by the energy available at the wireless rechargeable sensor.

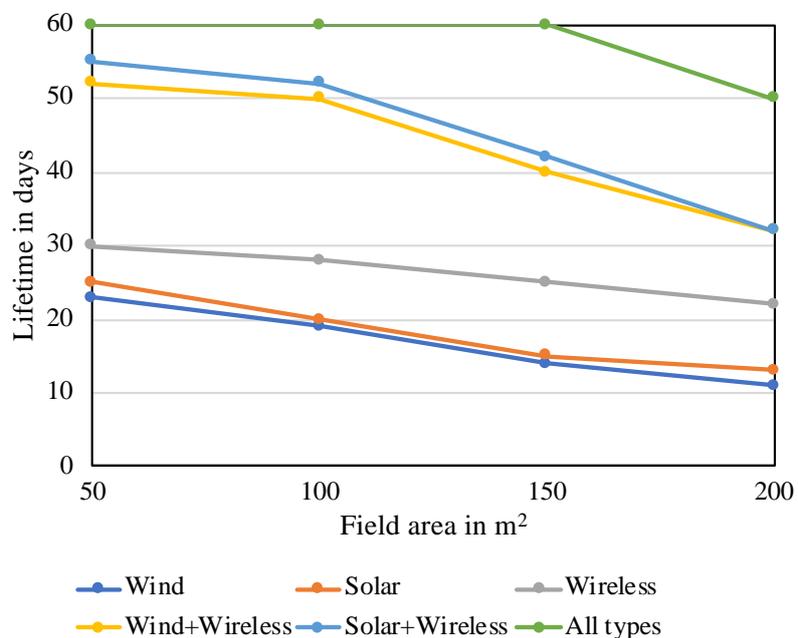


Figure 2. Field area vs. lifetime comparison of various sensors



Figure 2 shows the comparison of network lifetime with the simulation lifetime of 60 days. It represents the time expansion until the occurrence of the first depletion. Wireless charging or renewable energy is used to refill energy while certain energy depleted nodes turn into sleep mode temporarily during the waiting time. The operations are maintained and the network tasks are executed by the nodes that have energy. Combination of conventional and renewable energy is represented as all types. It is observed that the proposed model achieves a much longer lifetime when compared to the conventional models with a single energy source.

Figure 3 depicts the minimum EHBS required for maintaining the energy balance to ensure a continuous network operation. With the increase in field size, a linear increase in Joint is observed for minimum EHBS numbers. Network disruption may be caused and some coverage holes may be left while using random deployment.

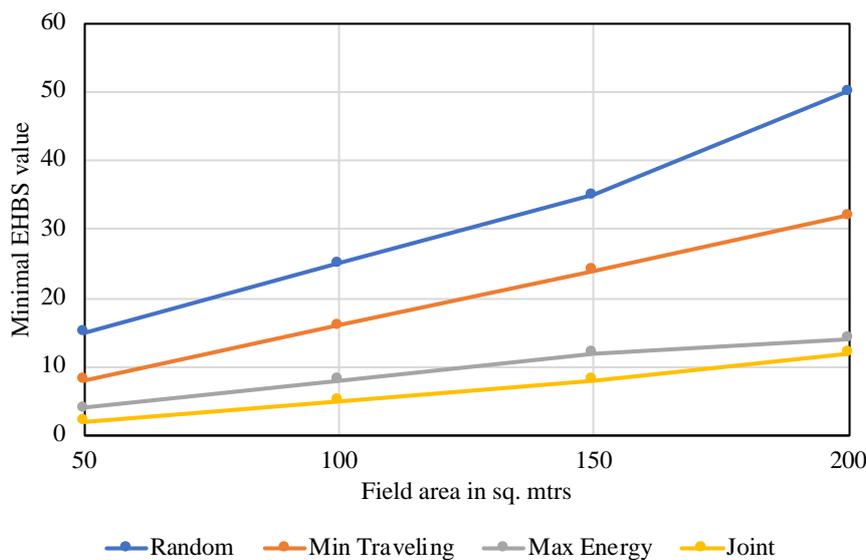


Figure 3. Energy Balance using minimal EHBS

5. Conclusion and Future Scope

A hybrid micro-energy harvesting model has been proposed in this paper that makes use of WSN for self-sustainable wireless mobile charging application. The manufacturing cost



of the system is reduced by addressing the maximum flow issue by obtaining the parameters of various sensors to derive the optimal composition. The EHBS deployment cost is considered and wireless charging is coordinated at the MC using a scheduling algorithm along with EHBS energy replenishment. Simulation results show that the energy efficiency and network lifetime of the system have improved considerably with the proposed model while considering the real weather data. Future work is directed towards enhancing the process of recharging with machine learning schemes. This may help in identifying the optimal energy that has to be distributed to each network node. Confirming the simulation results by implementing the solution on a real time platform for extensive testing is also planned as a future direction.

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