SCAPE: Safe Charging with Adjustable PowEr

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***Abstract*—Wireless power transfer technology is considered as one of the promising solutions to address the energy limitation problems for end-devices, but its incurred potential risk of electromagnetic radiation (EMR) exposure is largely overlooked by most existing works. In this paper, we consider the Safe Charging with Adjustable PowEr (SCAPE) problem, namely, how to adjust the power of chargers to maximize the charging utility of devices, while assuring that EMR intensity at any location in the field does not exceed a given threshold R_t. We present novel techniques to reformulate SCAPE into a traditional linear programming problem, and then remove its redundant constraints as much as possible to reduce computational effort. Next, we propose a distributed algorithm with provable approximation ratio $(1-\epsilon)$. Through extensive simulation and testbed experiments, we demonstrate that our $(1-\epsilon)$-approximation algorithm outperforms the Set-Cover algorithm by up to 23%, and has an average performance gain of 41.1% over the SCP algorithm in terms of the overall charging utility.**

I. Introduction

In recent years, wireless power transfer technology has been attracting great interests of industry and researchers. As a commercialized and controllable technology, it is one of the promising technologies to address the energy limitation problems for end-devices such as RFIDs, sensors, cell phones, laptops, vehicles and unmanned planes.

Though there has emerged a variety of works dedicated to energy efficiency issues with respect to wireless power transfer technology, most of them overlooked the potential risk of electromagnetic radiation (EMR) brought by this technology. Exposure to high EMR, however, has been widely recognized as a threat to human health. Its potential risks include but not limited to mental diseases, tissue impairment and brain tumor. In addition, there has been solid evidence that pregnant women and children are even more vulnerable to high EMR exposure [1]. For example, Gandhi *et al.* [2] found that children's heads absorb over two times of RF than adults, and their absorption of the skull's bone marrow can be ten times greater than adults. These facts suggest the need for considering EMR safety when applying wireless power transfer technology.

In this paper, we attempt to improve the overall charging performance under EMR safety concern, where chargers can continuously adjust their power level within an appropriate range. Basically, our objective is to maximize the overall charging utility of devices by adjusting the power of chargers, while assuring that no location has EMR intensity exceeding a given threshold.

Intuitively, this problem is quite challenging as the EMR safety requirement is imposed on every point in the field, which corresponds to an infinite number of constraints. To make the problem tractable, we present an approximation approach to reformulate the problem as a linear programming problem with limited constraints, and also devise a novel distributed approach to reduce the computational efforts of the problem. After that, we develop a $(1-\epsilon)$-approximation distributed algorithm to deal with this problem. To the best of our knowledge, this is the first paper considering the problem of maximizing the charging efficiency of the network under EMR safety concern, by adjusting the power of chargers. We formulate this problem as Safe Charging with Adjustable PowEr (SCAPE) problem.

II. Algorithm Design

Suppose that there is a set of n identical stationary wireless power chargers $S=\{s_1,s_2,\ldots,s_n\}$ and m rechargeable devices $O=\{o_1,o_2,\ldots,o_m\}$ distributed on a two-dimensional plane. The devices can harvest wireless power originated from the chargers and thus maintain normal working. We assume that all the chargers can continuously adjust its power level from 0 to a maximum power. We define adjusting factor $x_i\,(0\le x_i\le 1, i=1,\ldots,n)$ as the ratio of the current adjusted power to the maximum allowed power for the charger s_i. Thus, the received power by a device with a distance d from the charger is $x_iP(d)=x_i\frac{\alpha}{(d+\beta)^2}$ when $d\le D$, and 0 otherwise, where α and β are known constants. Besides, we assume the wireless power originating from multiple chargers received by a receiver is additive. We assume that each charger is aware of its location. Two chargers are neighbors to each other if and only if their coverage areas intersect. Each charger can simultaneously communicate with their neighbors wirelessly during charging process. For the charging utility model, we define the charging utility to be proportional to the charging power, namely $u(o_j)=C_1\sum_{i=1}^{n}P(d(s_i,o_j))x_i$, where $d(s_i,o_j)$ is the distance from the charger s_i to the device o_j, and C_1 is a predetermined constant. We adopt the EMR model which is proposed and experimentally verified by [1]. That is, the intensity of EMR is proportional to the received power there, i.e., $e(d)=C_2P(d)x_i$ where d is the distance and C_2 is the constant to capture the linear relation. Assuming EMR is also additive, the accumulated EMR at a location p is thus $e(p)=\sum_{s_i\in S}e(d(s_i,p))=C_2\sum_{s_i\in S}P(d(s_i,p))x_i$.

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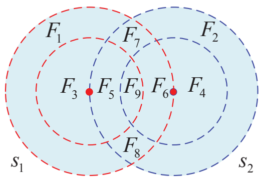

$1: 2x_1 \le 5$ $\quad$ $6: 2x_1 + 4x_2 \le 5$

$2: 2x_2 \le 5$ $\quad$ $7: 2x_1 + 2x_2 \le 5$

$3: 4x_1 \le 5$ $\quad$ $8: 2x_1 + 2x_2 \le 5$

$4: 4x_2 \le 5$ $\quad$ $9: 4x_1 + 4x_2 \le 5$

$5: 4x_1 + 2x_2 \le 5$

Fig. 1. Illustration of an example of constraint reduction

To control the EMR level over the field, we establish an appropriate EMR threshold R_t and require that EMR at any point p in the field should not exceed R_t. Our objective is to maximize the overall charging utility from all devices. Consequently, the Safe Charging with Adjustable PowEr problem (SCAPE) can thus be defined as an optimization problem subject to an infinite number of constraints, as the constraint in SCAPE is imposed on every point on the plane.

Near Optimal Algorithm. First of all, we use multiple piecewise constant segments $\varepsilon(d)$ with end points $\ell(1), ..., \ell(K)$ to approximate the EMR function $e(d)$. Then, we draw concentric circles with radius $\ell(1), ..., \ell(K)$ for each charger, respectively. The approximated EMR from the charger at any point between adjacent circles should be uniform. Finally, the whole network plane is thus partitioned into multiple sub-area faces. SCAPE is thus reformulated as a linear programming problem. Taking Fig. 1 as an example. The EMR function $e(d)$ is approximated by 2 piecewise constant segments, and therefore, the network plane is partitioned into 9 sub-area faces. Suppose the EMR threshold $R_t = 5$, the approximated charging power in inner and outer sub-areas is 4 and 2 respectively. We thus obtain 9 linear constraints as listed in Fig. 1.

Since the number of number of the faces will explode with a large network size and a small value of ϵ, we propose a distributed algorithm, DRR, to remove the "redundant constraints". In Fig. 1, the constraint 1-8 are identified as trivial constraints and removed. We prove that the DRR algorithm achieves the same performance as the corresponding centralized version. By simulation results, the DDR algorithm can reduce the number of constraints down to below 7.52%.

Next, we discuss how to develop a $(1-\epsilon)$ approximation algorithm. First, we divide the whole area into uniform squares with size $2D * 2D$, where D is the disk radius of chargers' coverage area. Apparently, by applying this partition method, the chargers in non-adjacent squares will not have their coverage areas intersected. As shown in Fig. 2, we group $m * m$ squares into a larger grid, which we call m-$grid$ for short. In Fig. 2, there are 6 m-$grid$s enclosed by blue dotted boundaries after grouping. To decompose the problem into minor ones and solve them in a distributed manner, we selectively turn off some chargers such that the entire area can be separated into several sub-areas. Fig. 2 shows an example that the chargers located in those white strips are switched off, then the whole area is re-partitioned into 12 sub-areas, each of which contains at most $m * m$ squares. Specifically, we require that each m-$grid$ adopt the same select-and-turn-off policy, namely, turning off all the chargers located at the i-th row and the j-th column of the m-$grid$, which is denoted by a two-tuple $\langle i, j \rangle$. In Fig. 2, each m-$grid$ adopts the policy $\langle 4, 4 \rangle$.

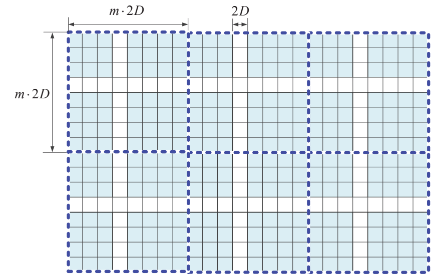

Fig. 2. Illustration of overall partition

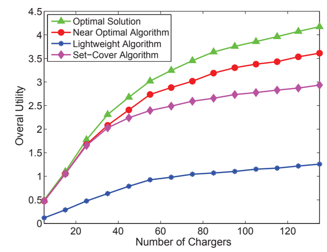

Fig. 3. Overall Utility vs. Charger Number

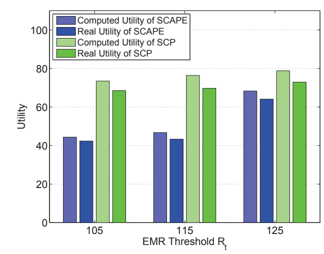

Fig. 4. Utility vs. EMR Threshold R_t

Consequently, in each partitioned sub-area, such as those 12 sub-areas in Fig. 2, we can apply a local linear programming method to determine the powers of the chargers inside independently of other sub-areas. This is because the nearest distance between any sub-areas is at least $2D$, which is sufficient to avoid the influence of EMR from chargers in other sub-areas. By intelligently determining the size of an m-$grid$ (i.e., m) and choosing the policy with the least performance loss, we can achieve a factor of $(1-\epsilon)$ of the optimum.

III. Simulation Results and Field Experiments

We examine the influence of the charger number on the overall utility. As shown in Fig. 3, the near optimal solution has an performance gain of up to 23.0% over the Set-Cover algorithm, which borrows the idea of Set-Cover, and its performance loss compared with the optimal solution (which is obtained by partitioning the area in a fine-grained way and solving the obtained linear programming problem in a centralized way) is no more than 13.5%. The light weight algorithm, which is executed purely locally, has the worst performance. We also build testbed and conduct field experiments to verify our theoretical findings. The testbed consists of 8 TX91501 power transmitters produced by Powercast, and 2 rechargeable sensor nodes. As illustrated in Fig. 4, we compare the utility computed based on sampling value with real utility under three different values of R_t for both SCAPE and SCP [1] algorithms. It can be observed that on average, the SCAPE algorithm is 41.1% better than the SCP algorithm. Besides, we measure the EMR values in the field, and find that all of them are successfully controlled and below the established EMR threshold R_t.

References

[1] H. Dai, Y. Liu, G. Chen, X. Wu, and T. He, "Safe charging for wireless power transfer," *(Accepted by INFOCOM'14)*.

[2] O. P. Gandhi *et al.*, "Exposure limits: The underestimation of absorbed cell phone radiation, especially in children," *Electromagnetic Biology and Medicine*, vol. 31, no. 1, pp. 34–51, 2012.