Multiple Stage Charging of Rechargeable Wireless Sensor Networks with a Directional Antenna

Celso Moraes and Dongsoo Har
Cho Chun Shik Graduate School of Green Transportation
KAIST
Daejeon, Republic of Korea
asura254@kaist.ac.kr, dshar@kaist.ac.kr

***Abstract*— Wireless sensor networks are finding widespread use nowadays with the development of Internet of Things (IoT) technology. Due to their wireless nature, these devices use batteries as their main source of power. This creates the problem of continuity of operation, because batteries have a limited lifetime. Therefore, sensors capable of performing energy harvesting are preferred. The harvested energy can be acquired from ambient or dedicated sources consisting of mobile chargers. This paper deals with a charging scheme for randomly distributed sensor nodes using a mobile charger. The charging scheme consists of a multiple-stage charging procedure, in which in each stage an energy goal for the target sensor nodes is set up. For charging in the first stage, all the sensor nodes are classified into clusters. The theory of an inclusion circle is used in this process. By clustering based on the inclusion circle, a sensor node that is located around the center of grouped sensor nodes is highly likely to be selected as the cluster head. The mobile charger only concentrates about charging the cluster heads. The charging path of the moving charger is determined according to the locations of cluster heads. In the following stages, new clusters are formed based on the energy level of the sensor nodes in the system, and a new target energy goal is set up for them.**

Keywords-Charging Sensors; Clustering;Wireless Sensor Networks; IoT; Energy HarFin thisvesting.

I. INTRODUCTION

The currently rapid development of the IoT has seen a large increase in the usage of sensor networks, generating challenges for the performance of this technology [1]. The provision of operating energy for IoT devices is becoming a major bottleneck in the development of this technology. Due to advances in chip design and in the deep submicron fabrication process, sensors that feature characteristics of low-power and low-cost are being adopted for a variety of applications, including mission-critical ones. These mission-critical applications, such as seismic activity [2][3], volcano temperature [4], space monitoring [5], disaster relief situation [6], human activity [7], and oceanic monitoring [8] instruments are associated with hard-to-reach sensor locations. In these environments, it is extremely dangerous and sometimes impossible to replace the batteries of the sensor nodes. Depletion of energy by a sensor node is a very important matter, one that highlights the importance of power provisioning. From this perspective, wireless (re)charging is a viable solution for sensor nodes capable of energy harvesting [9].

The rest of this paper is structured as follows. In Section II, we present the state of the art. In Section III, the proposed scheme of the rechargeable wireless sensor node with directional antenna is presented. Section IV details the results of the simulation. Finally, Section V concludes the paper.

II. STATE OF THE ART

There are many different ways to provide energy to sensor nodes in a rechargeable wireless sensor network. Fu et al. [10] presented a charging scheme with a mobile charger. The goal of their charging scheme is to find optimal locations of the mobile charger that can facilitate minimum charging time for all the sensor nodes to reach a target energy level. Linear programming is used to find the optimal spots at which the charger should be stationed over individual sojourn times. Madhja et al. [11] proposed a charging scheme employing multiple chargers, with two different classes of mobile chargers being used. The chargers that belong to the mobile charger class are responsible only for charging the infrastructure sensor nodes; the charger in the super charger class has the duty of charging the other chargers in the mobile charger class as well as the sensor nodes. Wang [12] presented a charging scheme with two different types of energy sources. The sensor nodes are clustered and the cluster heads have the capability of harvesting solar energy, while the other nodes are charged by mobile chargers transferring RF energy.

A charging scheme comprising multiple stages is proposed in this paper. Initially, using the concept of an inclusion circle, described by Moraes and Har [13], clusters and cluster heads are formed amongst the sensor nodes. Afterwards, the mobile charger will proceed to charge these cluster heads until a target energy level E_l is reached. The mobile charger can have either a directional or an omnidirectional antenna. After all the cluster heads reach the target energy level, a second charging stage is initiated. The old clusters are disregarded and new clusters are formed, but these clusters now include the energy level of each sensor

 ISBN: 978-1-61208-580-7

node as a criterion for being eligible for clustering. Only nodes under the target energy level E_l from the previous stage can participate in the new clustering procedure. A new charging stage is carried out by the mobile charger with the new cluster heads. The process of formation of new clusters and charging by the charger is repeated until all the sensor nodes in the system are charged to the final required level. This avoids favoring more centralized sensor nodes in the charging process, and the distributed nature of the charging procedure contributes to both decreasing the charging time and reducing energy expenditure

III. PROPOSED SCHEME

Consider that there are N_T sensor nodes randomly scattered in a square area. It is assumed that the sensor nodes in this case are fixed location nodes, for which the position of each node is known by the charger. Also, the charger has knowledge of each sensor node SoC (state of charge), which is a common assumption. The charger can move freely in the total service area.

The first step in the charging process is the initial formation of clusters in the system. Many clustering algorithms already exist in the literature, and for this work the clustering algorithm utilized was the one described in [13]. The number of clusters in this algorithm is determined by the distribution of the sensor nodes, and not predetermined before the clustering starts.

During the charging stages, the moving chargers only focus on supplying energy to the cluster heads, as was done in [13]. The time-varying change of charger location during the charging process can be modeled by concatenated discrete movements. The possible actions of the charger at each discrete time step are either to stay at the same location or to move to the next best location. The time interval Δt_c for the next movement is uniformly set at 2.5msec; distance r_m between the current location and the next optimal location is set at 0.05m during the simulations. If the next discrete movement to the next location circle occurs over a sizable time, and the location of the mobile charger is continuously shifted accordingly, the velocity of the mobile charger is (0.05m/2.5ms)=72km/hour. This circle is shown in Figure 1 (a). While the next location circle is concerned with the location of the mobile charger, the service sector with radius R_s , shown in Figure 1(b), is used to evaluate the amount of power received by the cluster heads, which influences the decision regarding the next optimal location on the next location circle.

The interior angle of each service sector is the beam width of the antenna, labeled as 2B; the bisector of the interior angle connects the charger and an undercharged cluster head. Therefore, the sector size increases as the antenna gain decreases. In the case of an omni-directional antenna, 2B is set to 360°.

Let $\theta_i(t)$, i=1,.., $N_{uch}(t)$, where $N_{uch}(t)$ is the total number of cluster heads at time t, be the θ of the i-th undercharged cluster head at time t. The $\theta_i(t)$ is formed by the horizontal line and the line connecting the charger and

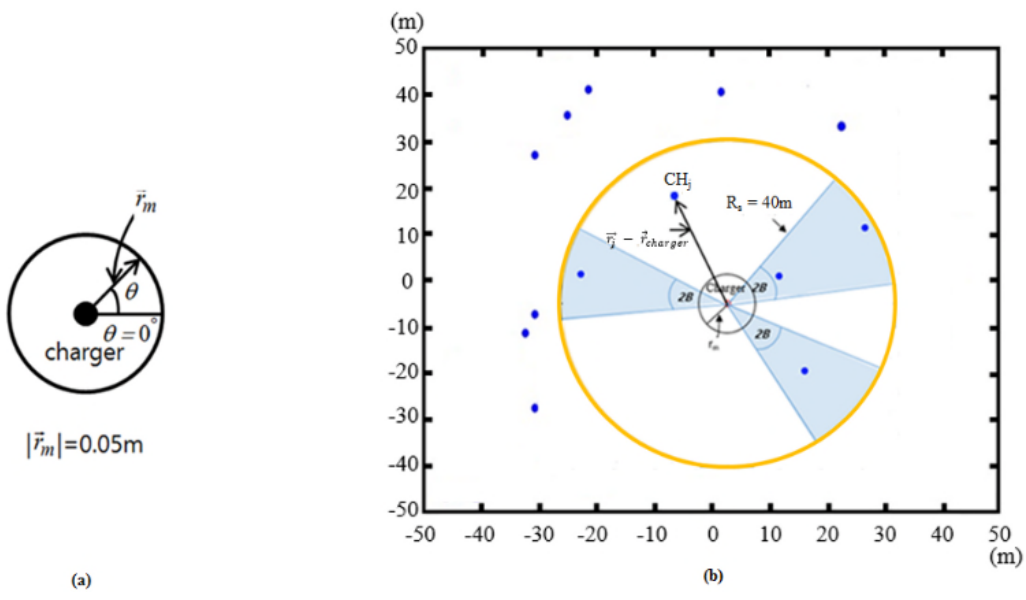

Figure 1. Next location circle and service sector for charging undercharged cluster heads: (a) next location circle; (b) sectors including undercharged cluster heads [13].

the i-th undercharged cluster head, as shown in Figure 1(b). For an angle $\theta_i(t)$ the number of undercharged cluster heads $N_{ss}(\theta_i(t))$ within the sector having a range of angle $(\theta_i(t)-B) \sim (\theta_i(t)+B)$ is considered to determine the movement of the charger. Then, the sum of the power $P_{ss}^A(\theta_i(t))$, received by the undercharged cluster heads within the i-th sector is given as [13]

$$P_{ss}^A(\theta_i(t)) = \sum_{s=1}^{N_{SS}(\theta_i(t))} P_r^A(\vec{r}_{is}(t), \vec{r}_{charger}(t) + \Delta\vec{r}_{\theta_i(t)}, \phi_{is}(t)) \quad (1)$$

with $i = 1,...,N_{uch}(t)$ and $s = 1,...,N_{ss}(\theta_i(t))$ and $N_{uch}(t) \geq N_{ss}(\theta_i(t))$. The $\vec{r}_{is}(t) = (x_{is}(t)\ y_{is}(t))$ is the location of the s-th undercharged cluster head within the i-th sector and the $\Delta\vec{r}_{\theta_i(t)} = (r_m \cos\theta_i(t)\ \ r_m \sin\theta_i(t))$ is the incremental vector from the location of the charger to a point on the next location circle at angle $\theta_i(t)$. Note that the locations of the undercharged cluster heads are functions of time t, because the undercharged cluster heads become overcharged over time one after another.

The next optimal location on the next location circle in terms of optimal $\theta_{opt}(t)$ can be mathematically expressed as [13]

$$\begin{aligned} \theta_{opt}(t) &= \arg\max_{\theta_i(t)} P_{ss}^A(\theta_i(t)) \\ &= \arg\max_{\theta_i(t)} \sum_{s=1}^{N_{SS}(\theta_i(t))} P_r^A(\vec{r}_{is}(t), \vec{r}_{charger}(t) + \Delta\vec{r}_{\theta_i(t)}, \phi_{is}(t)) \\ &= \arg\max_{\theta_i(t)} \sum_{s=1}^{N_{SS}(\theta_i(t))} g(\phi_{is}(t)) \frac{\alpha}{\left(d_{is}^{\theta}(t)+\beta\right)^2} \end{aligned} \quad (2)$$

IV. SIMULATION RESULTS

For the simulation results, the number of sensor nodes to be considered were set to be 100 and 200. The total size of the area occupied by the sensor nodes was 100 x 100 meters.

Figure 2 shows the probability density function (PDF) for the number of sensor nodes charged in the first stage charging for 100 sensor nodes. The number of sensor nodes charged in the first stage for 0 dB gain is much larger than that number for 12 dB gain. This happens because the beam width with 12 dB is much narrower, and the number of sensor nodes that will also be charged during the charging of the cluster heads is small, so the amount of energy needed by the undercharged sensor nodes in the following stages will be larger. For 0 dB, the beam width is omnidirectional, so many sensor nodes will also be charged alongside the cluster heads. Therefore, the number of sensor nodes that need to be charged and the amount of energy necessary to charge them will be significantly lower.

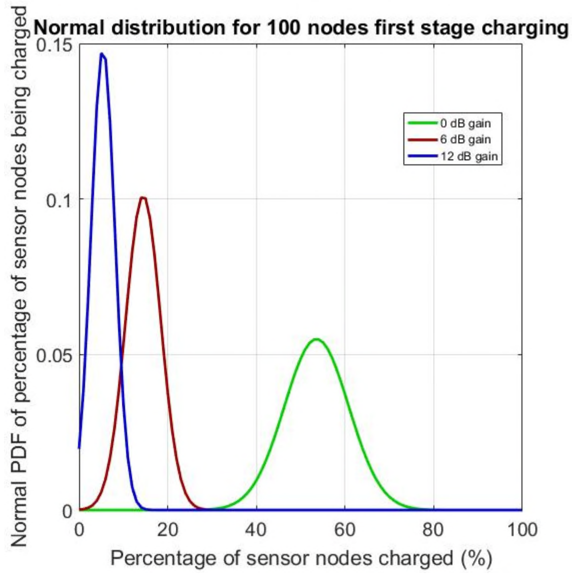

Figure 2. Probability density function of charged sensor nodes for 100 nodes in the first stage.

Figure 3 shows the PDF for the number of sensor nodes charged after the second stage charging. In this case, it is noticeable that there is a high probability that all sensor nodes will be charged with the 6 dB antenna. The 6 dB antenna appears to have the ideal tradeoff range value between 12 dB and 0 dB. At 6 dB the antenna presents a directional pattern, and so it will be able to focus on the cluster heads and speed up the charging process; however, because there is still a wide beam width angle for this antenna, many of the clustered nodes will also be charged during the charging of the cluster heads. To verify that this trend is maintained for larger numbers of sensor nodes, a sensor network with 200 nodes was simulated. Figure 4 shows that for 200 nodes the same trends continue, with the difference that for 0 dB and 6 dB the probability is more evenly spread out, providing the possibility of charging larger numbers of sensor nodes. Figure 5 shows the PDF for the second stage charging. For 200 nodes, it is shown in Figure 5 that the trend of 6 dB having the best trade-off value remains in place, with the only difference being that now the probability of all of them being charged is lower, which is understandable due to the higher number of sensor nodes in the system.

V. CONCLUSION

An alternative charging procedure for wireless sensor networks was proposed. The procedure consisted in splitting the charging time into stages so that a mobile charger could focus on cluster head sensor nodes instead of on the whole

ISBN: 978-1-61208-580-7

system, changing the assignments of cluster heads with increases of energy in the system. The procedure was shown to be able to charge sensors better by using a 6 dB gain antenna, due to the tradeoff between beam width and directional gain. The next steps will be to test the time and energy expenditure incurred with this charging process and compare those values with values of current models in the literature.

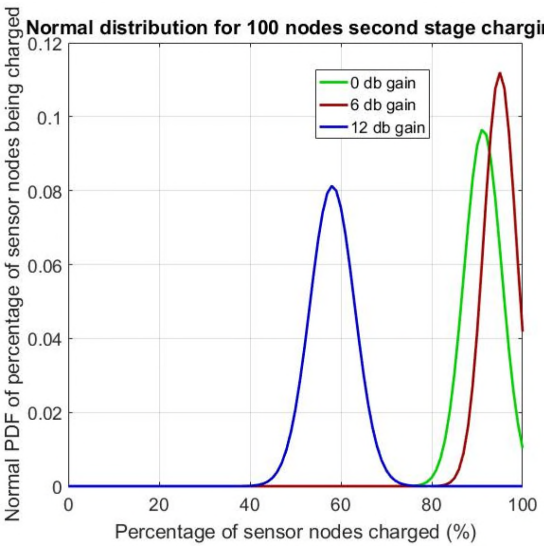

Figure 3. Probability density function of charged sensor nodes for 100 nodes in the second stage

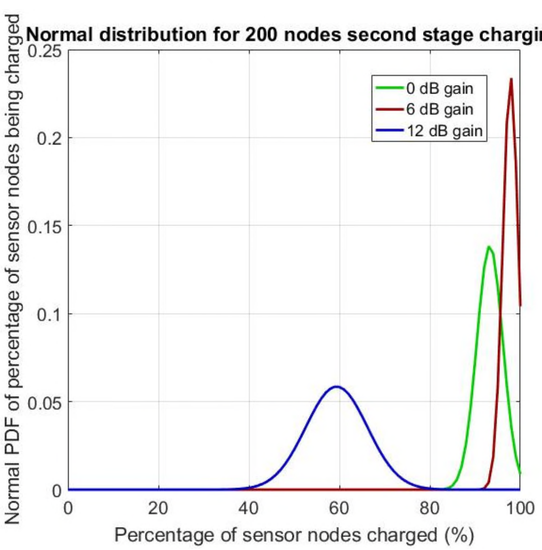

Figure 4. Probability density function of charged sensor nodes for 200 nodes in the first stage

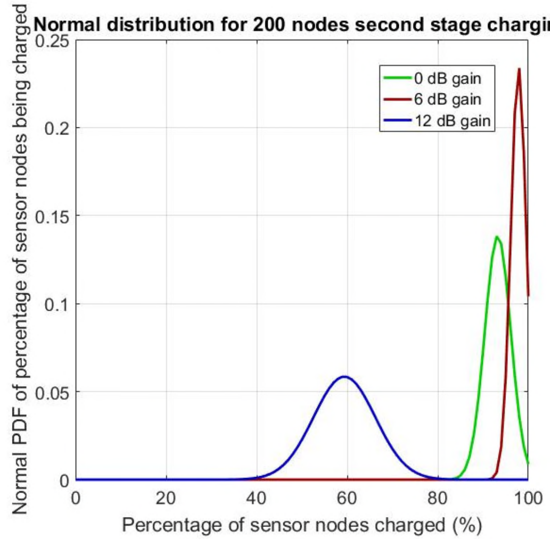

Figure 5. Probability density function of charged sensor nodes for 200 nodes in the first stage

REFERENCES

[1] F. Li and P. Xiong, "Practical Secure Communication for Integrating Wireless Sensor Networks Into the Internet of Things", IEEE Sensors Journal, Vol. 13, No. 10, Oct. 2013.

[2] A. Amditis, Y. Stratakos, D. Bairaktaris, M. Bimpas, S. Camarinopolos, and S. Frondistou-Yannas, "Wireless sensor network for seismic evaluation of concrete buildings," in Proc. 5th Eur. Workshop Struct. Health Monitor., Sorrento, Italy, July 2010.

[3] T. Torfs et al., "Low power wireless sensor network for building monitoring," IEEE Sensors J., Vol. 13, no. 3, pp. 909–915, Mar. 2013.

[4] G. Werner-Allen, K. Lorincz, M. Ruiz, O. Marcillo, J. Johnson, J. Lees, M. Welsh, "Deploying a Wireless Sensor Network on an Active Volcano," IEEE Internet Computing, Vol. 10, no. 2, pp. 18-25, 2006.

[5] H. F. Rashvand, A. Abedi, J.M. Alcaraz-Calero, P.D. Mitchell, and S. C. Mukhopadhyay, "Wireless sensor systems for space and extreme environments: A review," IEEE Sensors Journal, Vol. 14, no.11, pp.3955–3970, Sept. 2014.

[6] N. Aziz and K. Aziz, "Managing disaster with wireless sensor networks," IEEE Proceedings of 13th International Conference on Advanced Communication Technology (ICACT) , 2011, pp. 202–207, 2011.

[7] S. C. Mukhopadhyay, "Wearable Sensors for Human Activity Monitoring: A Review." IEEE Sensors Journal, Vol. 15, no. 3, pp. 1321-1330, 2015.

[8] C. Albaladejo et al., Torres, R. "Wireless Sensor Networks for Oceanographic Monitoring: A Systematic Review". *Sensors*, pp. 6948-6968, 2010.

[9] H. G. Lee and N. Chang, "Powering the IoT: Storage-less and converter-less energy harvesting," inProc. 20th Asia South Pacific Design Autom.Conf. (ASP-DAC), Jan. 2015, pp. 124–129.

[10] L. Fu, P. Cheng, Y. Gu, J. Chen and T. He, "Optimal Charging in Wireless Rechargeable Sensor Networks", *IEEE Trans. Veh. Technol*., Vol. 65, no. 1, pp. 278-291, Jan. 2016.

[11] A. Madhja, S. Nikoletseas and T. P. Raptis, "Hierarchical collaborative wireless charging in sensor networks", *IEEE WCNC*, pp.1285-1290, 2015.

[12] C. Wang, J. Li, Y. Yang and F. Ye, "A hybrid framework combining solar energy harvesting and wireless charging for wireless sensor networks".

[13] C. Moraes and D. Har "Charging Distributed Sensor Nodes Exploiting Clustering and Energy Trading," *IEEE Sensors Journal*, Vol. 17, no. 2, pp. 546-555, 2016.

 ISBN: 978-1-61208-580-7