# Charging wireless rechargeable sensor networks deployed in a rectangular street grid

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***Abstract*— Wireless charging remote sensors are becoming important for the sustainable operation of wireless sensor networks. An optimized charging scheme achieving minimum charging time is beneficial for low operational cost. In this paper, we investigate the charging scheme appropriate for wireless sensor networks deployed in a rectangular street grid of suburban and urban areas. The proposed charging scheme is intended to maximize the amount of energy received by the sensors by considering a sequentially optimized charging path. The path loss models used for the evaluation of energy received by a sensor are the Har-Xia-Bertoni model, the Hata model, and the empirical Friis model. It is shown that energy distribution of the sensors obtained by each path loss model substantially varies according to the path loss model.**

***Index Terms— Wireless rechargeable sensor networks, Path loss formula.***

## I. INTRODUCTION

Sustainable operation of sensor networks is critical for various applications. It is especially important for mission-critical wireless sensor networks. Therefore, the importance of charging sensor networks in a timely manner cannot be over-emphasized. Sensor devices operated with batteries usually have short lifetimes, and most wireless sensor networks cease operating when a small number or even one sensor node becomes energy-depleted. Also, the replacement of the sensors' batteries must be done manually, making such systems inefficient and sometimes impractical. Therefore, wireless charging has been recently receiving more attention as an alternative cost-effective method. [7]

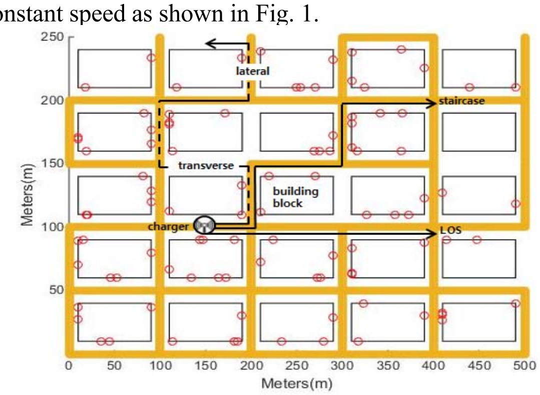
There are many charging schemes in the wireless charging field. Radio frequency (RF) remote charging with a small transmission antenna is gaining attention amongst current charging techniques for wireless rechargeable sensor networks (WRSNs). In addition, the beamforming technique, which can provide high directional gain for antennae, can facilitate increased charging efficiency. By using an omni-directional antenna, Fu et al. [1] suggested an optimal charging scheme. They assumed a freely movable charger that charges the sensor nodes deployed over the service area. The charger stops at calculated optimal locations, which have been chosen via a linear programming technique to charge all the sensor nodes in the lifetime of the wireless sensor networks. Cho et al. [2] suggested the use of a sink node with a directional antenna. Also, an energy harvesting scheme was proposed by Hwang et al. [5] to harvest electromagnetic energy by using a directional dipole antenna. Moreover, Chang et al. [6] used a mobile charger with a directional antenna to localize wireless rechargeable sensor networks.

In this paper, wireless charging is considered for real world applications. Sensors are usually low-power devices, especially sensors that are used for the Internet-of-Things (IoT). Therefore, in this paper, we propose a mobile charger to charge randomly distributed sensors on a rectangular street grid in suburban areas to achieve the target energy level by considering path loss. The performance analysis and simulation results compare the path loss models of the Har-Xia-Bertoni model [3], the Hata model [8], and the empirical Friis model in urban areas.

## II. SYSTEM MODEL

### A. Path loss modeling

The first procedure performed was the utilization of the Har-Xia-Bertoni model for microcells. Propagation paths are defined as four types. Each type of propagation path derives separate path loss formulas. Fig. 1 shows various propagation paths, namely, line-of-sight (LOS), lateral, transverse, and staircase. The charger sends an RF signal to the sensors in the service area. The charger moves in a rectangular street grid at constant speed as shown in Fig. 1.





978-1-5090-5753-5/16 $31.00 © 2016 IEEE
DOI 10.1109/APWC.on.CSE.2016.32

Fig. 1. LOS, lateral, transverse, and staircase test routes relative to the street grid [4] with optimal movement of the charger. The red circles represent wireless rechargeable sensors which are depleted at first, and the orange lines represent the path taken by the charger to charge the sensors.

The path loss equations are expressed below. The heights of the mobile antenna and the base station antenna are defined as $h_m$ and $h_b$, respectively, and both are measured in meters. Their separations, $R_k$ and $R_m$, are measured in units of kilometers and meters, respectively, and the carrier frequency $f_G$ has a unit of gigahertz in all the formulas.

The equations below express the path loss formulae for low-rise environments, and we assumed the building height is 12 meters, which is the average value for four-story buildings in suburban areas.

Transverse route:

$$\begin{aligned} P_L(R_k) &= [139.01 + 42.59 \log f_G] \\ &- [14.97 + 4.99 \log f_G] \operatorname{sgn}(\Delta h) \log(1 + |\Delta h|) \\ &+ [40.67 - 4.57 \operatorname{sgn}(\Delta h) \log(1 + |\Delta h|)] \log R_k . \end{aligned} \quad (1)$$

Lateral route:

$$\begin{aligned} P_L(R_k) &= [127.39 + 31.63 \log f_G] \\ &- [13.05 + 4.35 \log f_G] \operatorname{sgn}(\Delta h) \log(1 + |\Delta h|) \\ &+ [29.18 - 6.70 \operatorname{sgn}(\Delta h) \log(1 + |\Delta h|)] \log R_k . \end{aligned} \quad (2)$$

Staircase route:

$$\begin{aligned} P_L(R_k) &= [137.61 + 35.16 \log f_G] \\ &- [12.48 + 4.16 \log f_G] \operatorname{sgn}(\Delta h) \log(1 + |\Delta h|) \\ &+ [39.46 - 4.13 \operatorname{sgn}(\Delta h) \log(1 + |\Delta h|)] \log R_k . \end{aligned} \quad (3)$$

LOS route:

$$\begin{aligned} P_L(R_m) &= 20 \log(R_m) - 20 \log(\lambda) + 20 \log(4\pi). \end{aligned} \quad (4)$$

In this paper, we used a free-space path loss formula for an LOS environment. A signal was set with a 1 GHz frequency and a wavelength $\lambda$ of 0.333 m. We assumed that the sensors would be located on the walls of buildings at a height from the ground level of 3 m, and the height of the transmitting antenna from the ground level was assumed to be 6 m.

In the Hata model, suburban areas are described as

$$L_{su} = L_u - 2(\log_{10}(\frac{f}{28}))^2 - 5.4 \quad (5)$$

where

$L_{su}$ = path loss in suburban areas in units of decibels,

$L_u$ = average path loss in urban areas for a small city in units of decibels, and

$f$ = frequency of transmission in units of megahertz.

Also, $L_u$ is expressed by

$$\begin{aligned} L_u &= 69.55 + 26.16 \log_{10} f - 13.82 \log_{10} h_B \\ &- C_H + [44.9 - 6.55 \log_{10} h_B] \log_{10} d \end{aligned} , \quad (6)$$

$$C_H = 0.8 + (1.1 \log_{10} f - 0.7) h_M - 1.56 \log_{10} f , \quad (7)$$

where $h_B$ and $h_M$ are the heights of the base station antenna and mobile station antenna, respectively, in units of meters. Here,

$C_H$ = antenna height correction factor,

$d$ = distance between the base and mobile station in units of kilometers, and

$P_T$ = transmit power.

The empirical Friis path loss formula in urban areas is represented by

$$P_L(R_m) = P_T - 10 \log_{10}((\frac{\lambda}{4\pi})^2 \frac{1}{R_m{}^3}) . \quad (8)$$

*B. Charging modeling*

The path taken by the mobile charger is determined by the energy received from all of the sensors in the service area, which depends on the direction of the charger. The possible directions are right, left, up, and down. Because the unit street grid is not square, the maximum energy transfer to all of the sensors is determined by joules per unit meter (J/m). Let the objective function $T_c(PATH_i)$ be the charging time $T_c$ taken along a path, $PATH_i$. Optimization is achieved by minimizing the $T_c(PATH_i)$. The mathematical expression of the goal of optimization is

$$T_{c,\min} = \min_i T_c(PATH_i) \qquad \forall paths \quad (9)$$

subject to

$$\sum_{n=1}^{N_{PATH_i}} \int_{(n-1)\Delta t}^{n\Delta t} P_r(\vec{r}_j, \vec{r}_{charger}(t)) dt \geq TE_{\min} \quad j = 1, \ldots, N_s \quad (10)$$

where $N_s$ is the total number of sensors, and $P_r(\vec{r}_j, \vec{r}_{charger}(t))$ shows the power received by the j-th sensor with respect to the direction of charger movement. Here,

$TE_{\min}$ represents the target energy level of the sensors. The charging time $T_c(PATH_i)$ depends on the starting point of the path of the mobile charger. In our work, the optimal starting point was identified as an intersection which has the largest number of sensors in LOS. The variable $N_{PATH_i}$

indicates the number of time intervals $\Delta t$ associated with the path $PATH_i$. The number of time intervals for which the charger moves in a certain direction, determined at the previous intersection, is represented by $N_{PATH_i}$. Our charging scheme is based on sequential movements of the charger. Also, all the sensor nodes are considered when the direction of the charger is determined at the intersection. At each intersection, the charger determines the optimal direction to move. After the determination, for each time interval $\Delta t$, a discrete movement is made by the charger. When the direction is decided, the charger must move in that direction until it encounters another intersection.

## III. SIMULATION RESULTS

The target energy level was set as 1mJ. The number of sensors was set to 100. The transmit power was defined as 10 W. The service area was set to 500m x 250m. We set the velocity to 50km/h. Also, we compared results obtained with the Har-Xia-Bertoni model, the Hata model, and the empirical Friis model in suburban areas. In the first experiment, we compared how many sensor nodes are charged during 300 seconds. Fig. 2 shows the results. Fig. 2(a) shows the charged energy level after 300 seconds for Har's model for each sensor, Fig. 2(b) shows the results obtained using Hata's model, and Fig. 2(c) shows the results obtained with the empirical Friis' model. The results show that the number of overcharged sensors were 8, 13, 4, respectively.

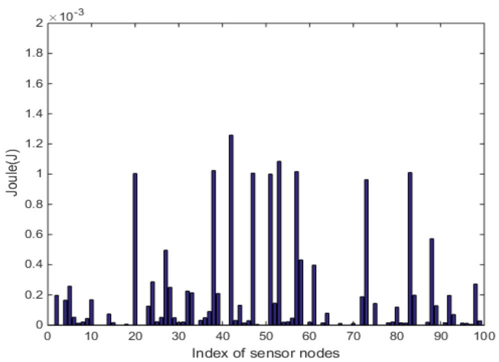



Fig. 2(a). Results obtained using Har's path loss formula for charging wireless rechargeable sensors.

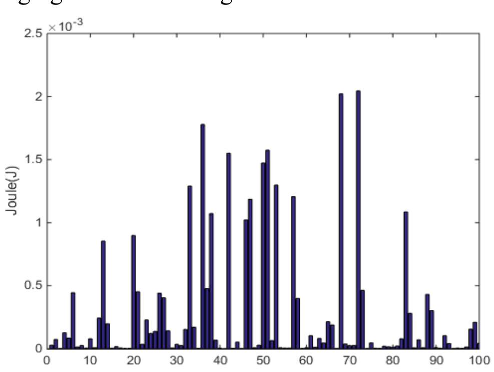



Fig. 2(b). Results obtained using Hata's path loss formula for charging wireless rechargeable sensors.

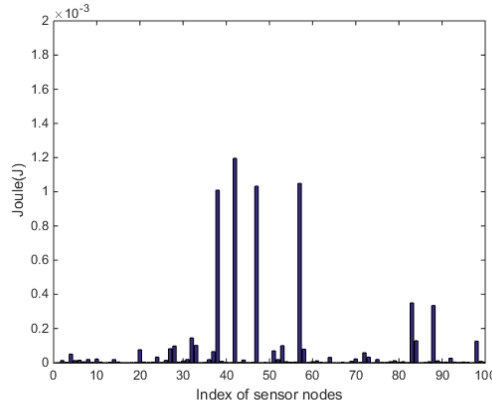



Fig. 2(c). Results obtained using empirical Friis's path loss formula(slope index = 3) for charging wireless rechargeable sensors.

Moreover, our second experiment shows charging aspects in relation to the path loss formulas. Fig. 3(a) shows the charged energy levels of sensors after 500 seconds, and Fig. 3(b) shows the levels after 1000 seconds applying the Har's path loss formula to 100 randomly distributed sensor nodes in the service area. The same procedure was carried out using the Hata model(Fig. 4(a), Fig. 4(b)) and the empirical Friis model(Fig. 5(a), Fig. 5(b)).

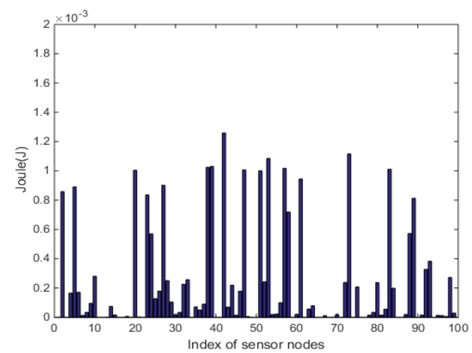



Fig. 3(a). Results obtained using Har's path loss formula. The total charging time was 500 seconds.

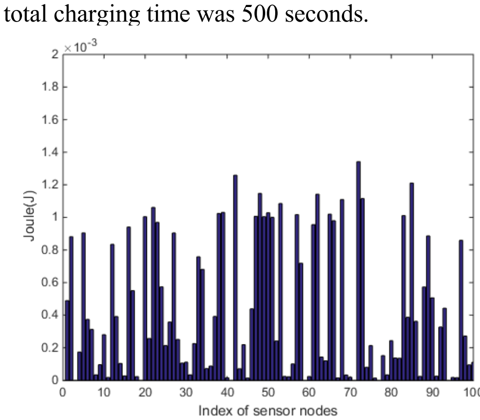


Fig. 3(b). Results obtained using Har's path loss formula. The total charging time was 1000 seconds.

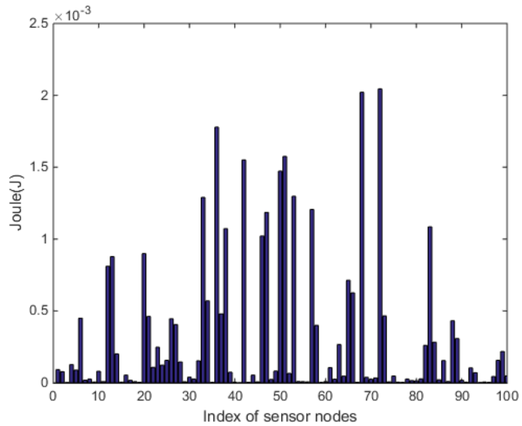



Fig. 4(a). Results obtained using Hata's path loss formula. The total charging time was 500 seconds.

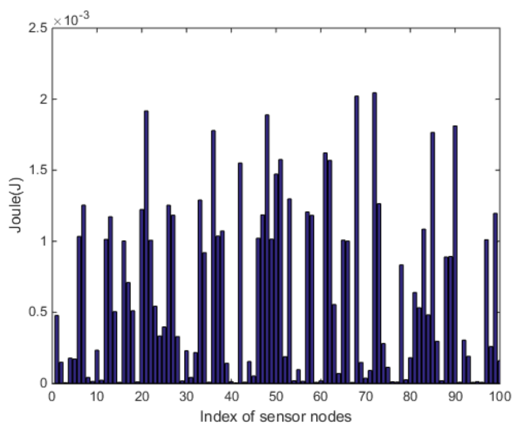



Fig. 4(b). Results obtained using Hata's path loss formula. The total charging time was 1000 seconds.

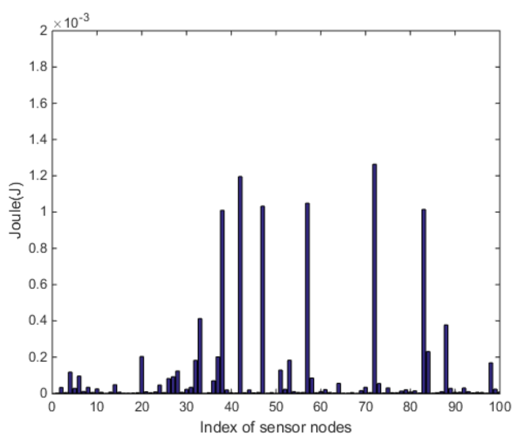



Fig. 5(a). Results obtained using empirical Friis' path loss formula. The total charging time was 500 seconds.

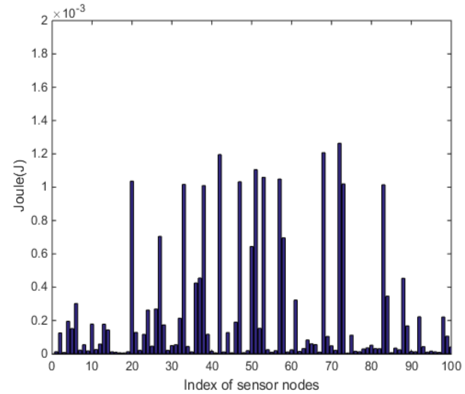



Fig. 5(b). Results obtained using empirical Friis' path loss formula. The total charging time was 1000 seconds.

## IV. CONCLUSION

This paper proposed a charging scheme for wireless sensor networks deployed in a rectangular street grid of suburban and urban areas by applying three different types of path loss formulas. Also, the simulation results demonstrate that the charging scheme using Hata's path loss formula is the most efficient for sensors in our scenario. Moreover, the different path loss models result in different energy levels for each sensor after a certain amount of charging time. Therefore, the selection of path loss model is important for wireless charging schemes in wireless sensor networks.

## REFERENCES


[1] 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.

[2] J. Cho, J. Lee, T. Kwon, and Y. Choi, "Directional Antenna at Sink (DAaS) to prolong network lifetime in Wireless Sensor Networks," Wireless Conference 2006 – Enabling Technologies for Wireless Multimedia Comm. (European Wireless), 12th Eur., Athens, Greece, pp. 1-5, Apr. 2006.

[3] D. Har, H. H. Xia, and H. L. Bertoni, "Path-Loss Prediction Model for Microcells," IEEE Trans. Veh. Technol., vol. 48, no. 5, pp. 1453-1462, Sep. 1999.

[4] H. H. Xia, H. L. Bertoni, L. R. Maciel, A. Lindsay-Stewart, and R. Rowe, "Microcellular Propagation Characteristics for Personal Communications in Urban and Suburban Environments," IEEE Trans. Veh. Technol., vol. 43, no. 3, pp. 743-752, Aug. 1994.

[5] I. Hwang, D. Kwon, D. Lee, J. Yu, and W. Lee, "EM/Light Hybrid Energy Harvesting with Directional Dipole Antenna for IoT Sensor," IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Vancouver, BC, pp. 1292 – 1293, Jul. 2015.

[6] Z. Chang et al.,"Localization in Wireless Rechargeable Sensor Networks Using Mobile Directional Charger," IEEE GLOBECOM, pp.1-6, 2015.

[7] M. K. Watfa, H. AlHassanieh, and S. Selman, "Multi-Hop Wireless Energy Transfer in WSNs", IEEE communications letters, vol. 15, no. 12, pp.1275-1277,Dec.2011.

[8] M. Hata, "Empirical formula for propagation loss in land mobile radio services," IEEE Trans. Veh. Technol., vol. 29, pp. 317–325, Aug. 1980.