This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

HYMN to Improve the Longevity of Wireless Sensor Networks

Hiroki Nishiyama[1,†] , Ahmed E.A.A. Abdulla[1,§], Nirwan Ansari[2,‡], Yoshiaki Nemoto[1,⊥], and Nei Kato[1,∓]
[1]Graduate School of Information Sciences, Tohoku University, Japan
[2]Advanced Networking Laboratory, ECE Department, NJIT, USA
E-mails: {bigtree[†], ahmed[§], kato[∓]}@it.ecei.tohoku.ac.jp, nirwan.ansari@njit.edu[‡], nemoto@nemoto.ecei.tohoku.ac.jp[⊥]

***Abstract*— Power aware routing in Wireless Sensor Networks (WSNs) focuses on the crucial issue of extending the network lifetime of WSNs, which are limited by low capacity batteries. However, most of the previously proposed power aware routing algorithms have an inherent problem, which is the isolation of the sink node due to the quick power exhaustion of nodes that are close to the sink. In this paper, we propose a solution, referred to as HYbrid Multi-hop routiNg (HYMN), which addresses this problem by combining two routing strategies, namely flat multi-hop routing and hierarchical multi-hop routing. The former method aims at minimizing the total power consumption in the network while the latter attempts to decrease the amount of transferred data traffic by utilizing data compression. We present a mathematical analysis on the effect of the hybrid location on the performance of HYMN, and also demonstrate the effectiveness of HYMN through extensive simulations.**

I. Introduction

In recent years, with the rapid development of wireless communication technology, and the miniaturization and low cost of sensing devices, it has become feasible to employ Wireless Sensor Networks (WSNs). WSN is a group of sensors equipped with transmission capable devices that are deployed in great numbers to monitor areas of interest. The general structure of a WSN is composed of a set of sensor nodes and a sink node. The role of sensor nodes is to gather data from their surroundings and send them to the sink node. In addition, the sensor nodes also assume the role of relaying data by virtue of infrastructureless nature of the network. On the other hand, the general role of the sink node, which can be mobile or immobile, is to act as a data assembly point in which data is extracted from the network.

A significant limitation of current sensor nodes is low battery capacity; as a direct consequence, efficient use of the sensor node's energy reserve is essential. The sensor node utilizes its built-in battery for communications and sensing; in the occasion of battery's exhaustion, the sensor's functionality stops. In such an occasion, part of the networks functionality is lost; also note that changing batteries of a large number of sensor nodes over wide areas in unsafe terrain is practically infeasible. Consequently, much research has been focused on maximizing the lifetime of the sensor network; however, most of the previous works do not take into account the isolation of the sink node, caused by the death of its surrounding nodes.

In the case where the sink is mobile, the load can be balanced over all nodes in the network, and the problem can be avoided by changing the migration route of the sink node to gather data from most of the living nodes as in KAT [1]; this problem cannot be avoided if the sink node is immobile. However, it is possible to mitigate this problem by controlling the routes of data transfer that largely affect the variance of individual power consumption of each sensor node, especially inside the high load areas. The objective of our research in this paper is to extend the network lifetime of WSNs via a better routing algorithm. In this paper, we propose a routing algorithm that assumes that the sink is immobile and demonstrate its effectiveness through mathematical analysis and computer simulations. The rest of this paper is organized as follows. Section II reviews existing multi-hop routing algorithms for WSNs, and describes the sink isolation problem. In Section III, we present our proposed method to rectify this problem, and provide mathematical analysis for the hybrid boundary. In Section IV, we evaluate the performance of our proposed method. Section V presents the conclusion.

II. Multi-hop routing algorithms for wireless sensor networks

In general, in order to maximize the WSN's lifetime, the total power consumption of the network should be minimized while ensuring fair power consumption among nodes. Much effort has been focused on WSN multi-hop routing algorithms, and many algorithms have been proposed. These may be widely categorized as flat multi-hop routing algorithms and hierarchical multi-hop routing algorithms.

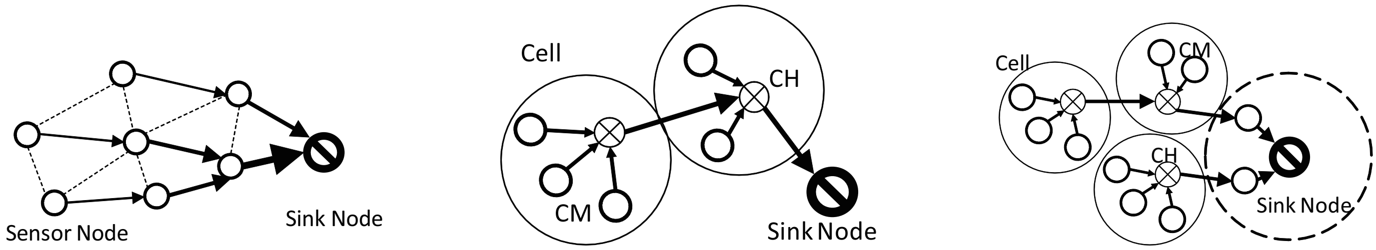
A. Flat multi-hop routing algorithms

Fig. 1(a) shows an example of how flat multi-hop routing is used to send data. In the figure, an arrow's thickness is proportional to the amount of data being sent over the corresponding link. Each sensor node has the ability to communicate over a bounded area with other sensor nodes. Link utilization differs greatly among different algorithms. For example, algorithms proposed in [2], [3] have been designed to minimize the total power consumption of the network as the objective; in this kind of algorithms, the cost of using a communication channel is defined by the following equations.

$$linkcost(i,j) = e_s(i) + e_r(j) \tag{1}$$

$$e_s(i) = \epsilon_1.d_{i,j}^2 + \epsilon_2 \tag{2}$$

$$e_r(j) = \epsilon_3. \tag{3}$$



(a) Flat multi-hop routing. (b) Hierarchical mutli-hop routing. (c) HYMN.

Fig. 1. Different categories of WSN multi-hop routing algorithms.

Here, $linkcost(i, j)$ is defined as the amount of energy consumed for sending a unit of data from node i to j. $e_s(i)$ is the energy consumed by node i while sending a unit of data to node j; this value is proportional to the square of $d_{i,j}$, which is the distance between nodes i and j. $e_r(j)$ is the energy consumed by node j in receiving a unit of data. ϵ_1, ϵ_2, and ϵ_3 are constants dependent on the sensor node communication circuits. By using the route where the sum of all link costs is minimized, the WSN's total power consumption can be minimized.

From a different perspective, these algorithms pose an inherent problem, i.e., certain nodes are over-burdened, and thus consume their energy in a rapid manner. An effective algorithm [4], which uniformly distributes power consumption over each node, aims to address this problem. The following equation is used to define the link cost.

$$linkcost(i, j)_{uniform} = \frac{linkcost(i, j)}{E_i^n}. \quad (4)$$

By using the residual power of the sending node, E_i, as the denominator of the link cost, the possibility of it being selected as a relay node decreases as its remaining energy decreases. Toh [4], set n to be 2. It is possible to uniformly distribute power consumption over individual nodes and at the same time to minimize overall power consumption. Besides the previously mentioned algorithm, others such as zP_{min} [5] and max–min T [6]–[9] have also been proposed.

B. Hierarchical multi-hop routing algorithms

In hierarchical multi-hop routing algorithms, sensor nodes assume different roles. Here, we briefly review the most notable example of hierarchical multi-hop routing algorithms, dubbed Low-Energy Adaptive Clustering Hierarchy (LEACH) [10], as an example for explanation.

LEACH is a two-layered hierarchical multi-hop routing algorithm. Each node can take on the role of a Cluster Head (CH) or Cluster Member (CM). In addition, each node's role can be renewed in a time interval, referred to as a round. In each round, each node can declare itself as a CH with a certain probability; otherwise, the node behaves as a CM. A network is divided into a number of clusters, called cells. CMs communicate with the CH that controls the cell to which they belong. Each CH aggregates and compresses the data received from CMs within the cell that it controls, and sends it to the sink node. In LEACH, since CHs initiate communication directly to the sink node, the transmission distance between the sink node and each CH tends to be large, thus draining the battery quickly; Multi-hop LEACH (M-LEACH) [11] has been proposed to mitigate this problem, as shown in Fig. 1(b). In M-LEACH, minimizing the power consumption of the CHs by means of multi-hop communications, can obviously delay their power exhaustion. While CHs are determined randomly in LEACH, changing the principle that governs how CHs are selected can decrease power consumption, as in HEED [12] and PEACH [13].

In hierarchical multi-hop routing algorithms, since the number of relay nodes used to convey data to the sink node is relatively smaller than that in flat multi-hop routing algorithms, the length of the communication distance of each hop becomes greater, and thus requiring higher power to transmit a unit of data. Nevertheless, hierarchical multi-hop routing algorithms are a promising approach in terms of their capability to use data compression to reduce the power consumption of the network by reducing the data flow.

C. Sink node isolation problem in WSNs

In multi-hop routing algorithms, nodes that are within the maximum transmission range of the sink node form the subset of nodes that enable the sink node to gain connectivity to the network. We refer to the area, which contains these nodes, as the Sink Connectivity Area (SCA). As illustrated in Fig. 1(a), since the amount of data relayed per node increases as nodes become closer to the sink node, leading to quicker power exhaustion of these nodes than others. When all of the nodes located in SCA die, the sink node can no longer gather data from other alive nodes due to the lack of available routes between the sink node and the rest of the network; this is equivalent to the breakdown of the network deployed to gather sensed data. In other words, to evaluate the network lifetime exactly, it is essential to take into account the influence of the sink node isolation problem, while most of previous works have only investigated the surviving rate of nodes in the network. Therefore, we propose an algorithm designed with the consideration of the impact of the sink node isolation problem in order to improve the longevity of the network.

III. Hybrid multi-hop routing algorithm

In general, since the number of sensor nodes in the SCA is much smaller than that outside the SCA, the amount of data generated by the nodes in the SCA can be negligible as compared to the volume of data flowing into the SCA from outside. This implies that most of the power consumption

978-1-4244-5637-6/10/$26.00 ©2010 IEEE

TABLE I
Problem preliminaries.

Parameter	Definition
d_F	Average distance between nodes in flat multi-hop routing
d_{CH}	Average transmission distance for CHs
d_{CM}	Average distance between CH and CMs
$e(d)$	Power consumption over distance d.
R_0	SCA radius
α	Factor of hybrid boundary $0 \leq \alpha \leq K$
K	Factor of sensing field
ρ	Node density
δ	CH ratio $0 < \delta < 0.5$
m	Messege size
γ	Data compression ratio $0 < \gamma \leq 1$

in the SCA is due to transferring the data that comes from outside the SCA to the sink node. In other words, in order to limit the power consumption in the SCA, the amount of data flowing into the SCA needs to be reduced, and/or the power consumption to relay the data from outside the SCA to the sink node needs to be minimized. In fact, the proposed scheme, referred to as HYbrid Multi-hop routiNg (HYMN), illustrated in Fig. 1(c), aims to achieve the effect of both solutions by employing a hierarchical multi-hop routing algorithm outside the SCA and using a flat multi-hop routing algorithm inside the SCA.

A. Routing outside the SCA

Since the transmission power is proportional to the volume of data, it is important to reduce the volume of data that enters the SCA; this can be achieved by using a data compression mechanism. If there is any relationship among data, it can be aggregated and compressed; the compression ratio depends on the correlation of the data and can be derived from the maximum mutual information. In the case of environmental monitoring which collects information on temperature, humidity, and atmospheric pressure, it has been widely known that data collected from neighboring areas have a strong correlation that can lead to high compression ratio. From the above discussion, HYMN employs a hierarchical multi-hop routing which is an appropriate strategy to perform efficient data compression to reduce the amount of data flowing into the SCA.

B. Routing inside the SCA

In the SCA, the most important aspect in routing is to minimize the power consumption while transferring the data coming from outside the SCA to the sink node. Fortunately, this can be completely achieved by adopting a flat multi-hop routing scheme in the SCA.

C. Optimal location of hybrid boundary

Herein, we consider the optimal location of the hybrid boundary, where the employed routing algorithm is switched from flat to hierarchical and vice versa. To derive the mathematical formulation representing the effect of the hybrid boundary on the performance of power consumption in the SCA, we introduce an analytical model, as shown in Fig. 2 in which the parameters are listed in Table I. Assume that nodes

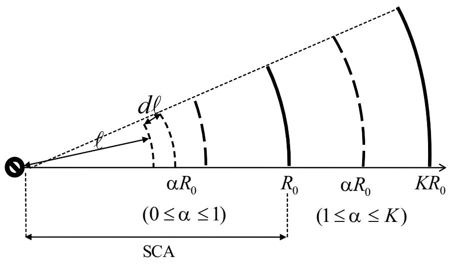


Fig. 2. Considered mathematical model.

are uniformly distributed over the network, and the maximum transmission range is sufficiently larger than the average distance between two neighboring nodes. We divide this problem into two cases, the case where the hybrid boundary is outside the SCA, and that inside the SCA.

1) The hybrid boundary is outside the SCA: when $1 \leq \alpha \leq K$, the total power consumption in the SCA, E^{OUT}, is composed of two parts as follows:

$$E^{OUT} = E_S^{OUT} + E_R^{OUT}, \tag{5}$$

where E_S^{OUT} and E_R^{OUT} denote the energy consumed to transfer the data that originated from within the SCA to the sink node, and the energy consumed for relaying data coming from outside the SCA to the sink node, respectively. E_S^{OUT} can be formulated as follows:

$$\begin{aligned} E_S^{OUT} &= \int_0^{R_0} m 2\ell\pi d\ell \rho \frac{\ell}{d_F} e(d_F) \\ &= \frac{2}{3}\pi m \rho \frac{e(d_F)}{d_F} R_0^3, \end{aligned} \tag{6}$$

where the terms, $2\ell\pi d\ell\rho$ and ℓ/d_F, represent the number of nodes within the ring with width equal to $d\ell$ and the expected hop count between the ring and the sink node, respectively. On the other hand, E_R^{OUT} can be formulated as follows.

$$\begin{aligned} E_R^{OUT} &= \{\pi(K^2 - \alpha^2)R_0^2 \rho m \gamma + \pi(\alpha^2 - 1)R_0^2 \rho m\} \frac{R_0}{d_F} e(d_F) \\ &= \pi m \rho \; R_0^3 \frac{e(d_F)}{d_F} \{K^2\gamma + (1-\gamma)\alpha^2 - 1\}, \end{aligned} \tag{7}$$

where the terms, $\pi(K^2 - \alpha^2)R_0^2\rho$ and $\pi(\alpha^2 - 1)R_0^2\rho$, represent the number of nodes in the hierarchical multi-hop routing area and the flat multi-hop routing area outside the SCA, respectively. R_0/d_F is the expected hop count between the SCA and the sink node. As evident from Eq. (7), E_R^{OUT} is a monotonic increasing function of α, implying that the optimal hybrid boundary exists within the SCA, i.e., $0 \leq \alpha \leq 1$.

2) The hybrid boundary is inside the SCA: when $0 \leq \alpha \leq 1$, E^{IN}, the energy consumption in the SCA, is composed of four parts as follows:

$$E^{IN} = E_S^F + E_S^{CM} + E_S^{CH} + E_R^{IN}, \tag{8}$$

where E_S^F denotes the energy consumed to transfer the data that originated from within the interior of αR_0 to the sink node; E_S^{CM} is the energy consumed when CMs send data originated from the SCA to the CHs; E_S^{CH} is the energy

TABLE II

Configuration of simulation environment.

Parameter	Value
ϵ_1	2×10^{-7} [J/packet/m^2]
ϵ_2, ϵ_3	2×10^{-6} [J/packet/m^2]
Data compression rate	0.2
Probability of node becoming a CH	0.4
Number of nodes	500
Maximum transmission range	600 [m]
Data transmission rate	1 [packet/round]
Initial energy of each node	100 [J]

consumed by CHs in the SCA when they send aggregated data to the sink node; E_R^{IN} is the energy consumed for relaying data coming from outside the SCA to the sink node. They can be formulated as follows:

$$E_S^F = \int_0^{\alpha R_0} m 2\ell\pi d\ell \rho \frac{\ell}{d_F} e(d_F) = \frac{2}{3}\pi m \rho \frac{e(d_F)}{d_F} \alpha^3 R_0^3, \quad (9)$$

which similarly follows the formulation of Eq. (6).

$$E_S^{CM} = m\pi R_0^2(1-\alpha^2)\rho(1-\delta)e(d_{CM}), \quad (10)$$

where the term $\pi R_0^2(1-\alpha^2)\rho(1-\delta)$ represents the number of CMs in the SCA.

$$E_S^{CH} = \int_{\alpha R_0}^{R_0} m\gamma 2\ell\pi d\ell \rho \left\{ \frac{(\ell - \alpha R_0)}{d_{CH}} e(d_{CH}) + \frac{\alpha R_0}{d_F} e(d_F) \right\} = \frac{1}{3}\pi m \rho \gamma R_0^3 \times \left\{ (\alpha^3 - 3\alpha + 2)\frac{e(d_{CH})}{d_{CH}} + 3\alpha(1-\alpha^2)\frac{e(d_F)}{d_F} \right\}, \quad (11)$$

where the terms, $(\ell - \alpha R_0)/d_{CH}$ and $\alpha R_0/d_F$, are the hop count in hierarhical and in flat routing areas, respectively.

$$E_R^{IN} = m\gamma\pi R_0^2(K^2-1)\rho \times \left\{ \frac{(1-\alpha)R_0}{d_{CH}} e(d_{CH}) + \frac{\alpha R_0}{d_F} e(d_F) \right\}, \quad (12)$$

where the terms, $(1-\alpha)R_0/d_{CH}$ and $\alpha R_0/d_F$ are the hop count, for CHs in the hierarchical, and for nodes in flat routing areas, of the SCA, respectively. E^{IN} can be rewritten in the following polynomial form,

$$E^{IN} = A_1\alpha^3 + A_2\alpha^2 + A_3\alpha + A_4, \quad (13)$$

where the signs of the coefficients are $A_1 > 0$, $A_2 < 0$, $A_3 < 0$, and $A_4 > 0$. In order to understand the shape of this function, we apply the first derivative test, as shown below,

$$(E^{IN})' = 3A_1\alpha^2 + 2A_2\alpha + A_3. \quad (14)$$

If α is 0, $(E^{IN})' = A_3 < 0$ which reflects that the function has a negative gradient, and from Eq. (7), we conclude that the optimal hybrid location is between the sink and the SCA. To locate the optimal hybrid boundary, we conduct computer simulations as will be discussed next.

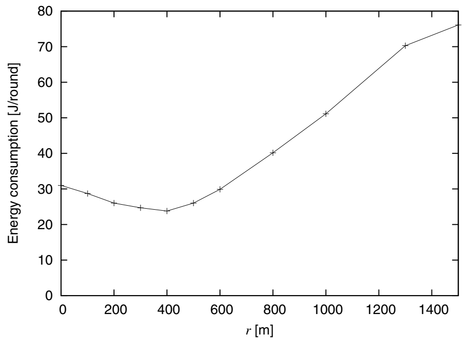


Fig. 3. Impact of hybrid boundary location on the performance of HYMN.

IV. Performance evaluation

A. Experiment setup

Network Simulator version 2 (NS2) [14] was used to evaluate the performance of HYMN. Sensor nodes are randomly deployed in the circular sensing field centered on the sink node. The sensing field radius is set to a relatively high value of 1500m. Table II shows the configuration of the simulation environment where the value of each parameter is set according to the configurations reported in References [4], [10], [11]. Since the maximum transmission range of the nodes is 600m, the SCA is also circle with a radius of 600m centered on the sink node. Each experiment was conducted 20 times, and the results are averaged over all different node arrangements. We assume that nodes are distributed without large deviation of node density, i.e., the number of nodes in the SCA does not deviate much in the conducted experiments. In the proposed technique, M-LEACH and Toh's method have been employed outside and inside of the SCA, respectively. Also, these two notable multi-hop routing algorithms have been used for comparison.

B. Impact of the hybrid boundary location on performance

To clarify the influence of the hybrid boundary location on the performance of HYMN, we conducted simulations by varying the distance, r, between the sink node and the hybrid boundary, and examined the changes in the power consumption in the SCA. Fig. 3 shows that the optimal hybrid boundary exists in the SCA, i.e., when r is equal to 400m. Thus, we use the value of 400m as the value of hybrid boundary to evaluate the performance of HYMN.

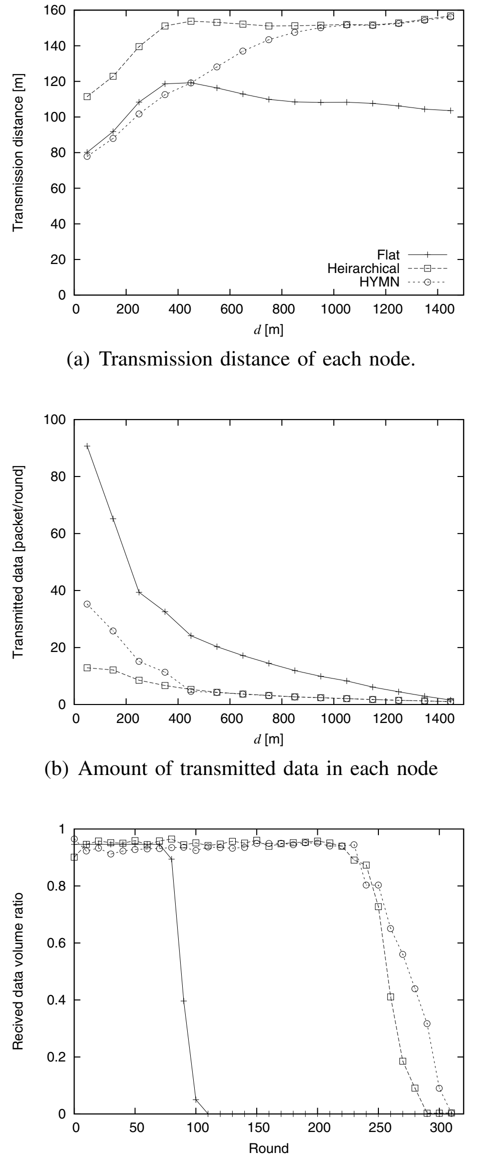
C. Performance comparison

To evaluate the performance of HYMN with respect to both flat and hierarchical multi-hop routing algorithms, the transmission distance of each node, and the amount of traffic relayed by each node in each strategy is investigated. Fig. 4(a) depicts the average transmission distance of each node at distance d from the sink. It can be observed that the hierarchical multi-hop routing algorithm incurs a larger transmission distance when compared with flat multi-hop routing. In addition, it should be noted that, in HYMN, the communication distance is different between the outside and the inside of the hybrid boundary due to the different algorithms used in each area.

Fig. 4(b) shows the amount of relayed traffic. It is clear that the amount of relayed traffic in hierarchical multi-hop routing is less than that of flat multi-hop routing.

From the above discussion, the results validate that by decreasing the amount of traffic, while simultaneously using a shorter transmission distance, HYMN is able to lower the power consumption in the SCA, as shown in Fig. 3, i.e., hierarchical and flat multi-hop routing algorithms correspond to r equal to zero and r equal to 1500m, respectively.

Finally, Fig. 4(c) shows the change in the ratio between the volume of data received by the sink to the volume generated by the network with respect to rounds, where a round refers to a time slot in which every node in the network sends a packet to the sink node. We can see that flat multi-hop routing results in the earliest sink node isolation. On the other hand, HYMN succeeds in avoiding sink node isolation for the longest period. It is evident that by avoiding sink node isolation, HYMN is able to extend the operation lifetime of the network.



(a) Transmission distance of each node.

(b) Amount of transmitted data in each node

(c) Change in ratio of data received to data sent with time

Fig. 4. Performance comparison among three different routing algorithms.

V. Conclusion

In this paper, we have proposed a routing algorithm, HYMN, which prolongs the operation lifetime of wireless sensor networks by mitigating the sink node isolation problem. Sensor network routing algorithms can be categorized into two classes, flat multi-hop routing algorithms which minimize the total power consumption in the network, and hierarchical multi-hop routing algorithms which reduce the amount of traffic flowing through the network by using data aggregation and compression mechanisms; both approaches do not take into account the sink node isolation caused by the high load on nodes close to the sink. We proposed HYMN to mitigate this problem by combining flat and hierarchical multi-hop routing algorithms. Through mathematical analysis, the effect of the hybrid boundary has been clarified. Finally, the performance of HYMN has been validated through extensive simulations. The results show that HYMN is a promising solution to the sink node isolation problem.

References

[1] H. Nakayama, N. Ansari, A. Jamalipour, and N. Kato, “Fault-resilient Sensing in Wireless Sensor Networks,” *Computer Communications, Special Issue on Security on Wireless Ad Hoc and Sensor Networks.*, vol. 30, no. 11-12, pp. 2376-2384, Sep. 2007.

[2] S. Singh, M. Woo, and C.S. Raghavendra, “Power aware routing in mobile ad-hoc networks,” in *Proc. of ACM/IEEE MobiCom.*, pp. 181-190, Dallas, USA, Oct. 1998.

[3] V. Rodoplu and T.H. Meng, “Minimum-energy mobile wireless networks revisited,” *IEEE J. Selected Areas Communications*, vol. 17, no. 8, pp. 1333-1344, Aug. 1999.

[4] C.K. Toh, “Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks,” *IEEE Communications Mag.*, vol. 39, no. 6, pp. 138-147, Jun. 2001.

[5] J. Aslam, Q. Li, and D. Rus,“Three power-aware routing algorithms for sensor network,” *Wireless Commun. and Mobile Computing,*, vol. 3, no. 2, pp. 187-208, Mar. 2003.

[6] J.H. Chang and L. Tassiulas, “Maximum lifetime routing in wireless sensor networks,” *IEEE/ACM Trans. Networking*, vol. 12, no. 4, pp. 609-619, Aug. 2004.

[7] R. Madan and S. Lall, “Distributed algorithms for maximum lifetime routing in wireless sensor networks,” in *Proc. of IEEE GLOBECOM*, vol. 2, pp. 748-753, Dallas, USA, Nov./Dec. 2004.

[8] A. Sankar and Z. Liu, “Maximum lifetime routing in wireless ad-hoc networks,” in *Proc. of IEEE INFOCOM*, vol. 2, pp. 1089-1097, Hong Kong, China, Mar. 2004.

[9] Y. Xue, Y. Cui, and K. Nahrstedt,“Maximizing lifetime for data aggregation in wireless sensor networks,” *Mobile Networks and Applications*, vol. 10, no. 6, pp. 853-864, Dec. 2005.

[10] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan,“An application specific protocol architecture for wireless microsensor networks,” *IEEE Trans. Wireless Communications*, vol. 1, no. 4, pp. 660-670, Oct. 2002.

[11] V. Mhatre and C. Rosenberg,“Homogeneous vs. heterogeneous clustered sensor networks: a comparative study,” in *Proc. of IEEE ICC*, vol. 6, pp. 3646-3651, Paris, France, Jun. 2004.

[12] O. Younis and S. Fahmy, “Heed: a hybrid, energy-efficient, distributed clustering approach for ad-hoc sensor networks,” *IEEE Trans. Mobile Computing*, vol. 3, no. 4, pp. 366-379, Oct./Dec. 2004.

[13] S. Yi, J. Heo, Y. Cho, and J. Hong,“Peach: power efficient and adaptive clustering hierarchy protocol for wireless sensor networks,” *Computer Communications*, vol. 1, no. 4, Oct. 2004, pp. 193-208.

[14] The Network Simulator - ns-2 [Online]. Available: http://www.isi.edu/nsnam/ns/.