HYMN to Improve the Scalability of Wireless Sensor Networks

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***Abstract*— Power-aware routing algorithms in Wireless Sensor Networks (WSNs) aim to solve the key issue of prolonging the lifetime of resource-constrained ad-hoc sensor nodes. Contemporary WSN routing algorithm designs have severe limitations on their scalability; that is, large-scale deployments of WSNs result in relatively shorter lifetimes, as compared to small-scale deployments, primarily owing to rapid sink node isolation caused by the quick battery exhaustion of nodes that are close to the sink. In this paper, we analyze the scalability limitations of conventional routing algorithms and compare them to those of our recently proposed Hybrid Multi-hop routiNg (HYMN) [1]. We mathematically analyze HYMN and show the relationship between network size and routing algorithm scalability. Additionally, through extensive simulations, we show that HYMN scales considerably better in terms of network connectivity.**

I. Introduction

Recent advances in the wireless communications technology and nanotechnology have facilitated the deployment of Wireless Sensor Networks (WSNs), which consist of inexpensive sensor-equipped wireless-transmission capable nodes that are deployed in large numbers to monitor areas of interest. Applications range from environmental, which include measuring temperature readings, to military, which include detecting adversary movements.

The structure of a WSN, as illustrated in Fig. 1, is made up of sensor nodes and a sink node. The sensor nodes collect data from their surroundings and forward them to the sink node. Additionally, since ad-hoc networking is used to compensate the lack of infrastructure support, individual nodes act as routers by assuming the packet forwarding role. The sink node acts as the gateway for the WSN, an assembly point from which the user extracts data from the WSN.

Sensor nodes in WSNs are battery-powered devices. Whenever the battery of a sensor node is used up, the node can no longer operate and partial loss of network functionality occurs, replacement of a large number of batteries in some applications is impractical, and hence power-efficient technologies are required to insure long lifetimes of WSNs. Consequently, much research effort has been put into power-aware routing algorithms for WSNs, and the scalability of these algorithms has been evaluated from different perspectives. In this paper, we focus on routing algorithm designs that have good scalability for large-scale WSN deployments. Our notion of scalability is one that has not received sufficient treatment in previous research, described as follows. A scalable WSN routing algorithm must work well as the network grows large. As the network size grows, the volume of data relayed to the sink node grows, and consequently the load on the network increases, especially on nodes that are close to the sink, and hence the death rate of sensor nodes increases, thus leading to early sink node isolation. As a result, the lifetime of a large WSN deployment is shorter than that of a small WSN deployment.

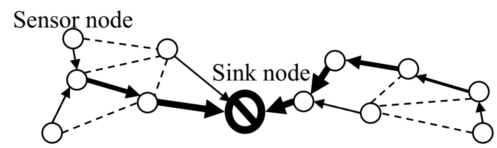

Fig. 1. Flat multi-hop routing.

This problem can be easily overcome in the case where the sink node is mobile so as to avoid sink node isolation as in [2], [3]. In [4], multiple sinks are deployed to divide the network load in a more uniform manner. In this work, we consider a single immobile sink routing algorithm that scales well as the network grows larger. What is left of this paper is organized in the following manner. Section II examines existing multi-hop routing algorithm designs for WSNs, in which we study scalability limitations in current WSN routing algorithm designs. In Section III, we present our proposed method to rectify this problem, and provide a mathematical model for power consumption. In Section IV, we evaluate the performance of our proposed method. We finalize in Section V with a conclusion.

II. Power-aware multi-hop routing algorithms for wireless sensor networks

To prolong the longevity of a WSN, the energy consumed by the WSN per unit of data collected from the monitored area must be minimized. Many routing algorithm have been proposed trying to meet this objective. These can be widely classified as flat multi-hop routing algorithms and hierarchical multi-hop routing algorithms. In the following two subsections, we examine these two categories.

A. Flat multi-hop routing algorithms

This category of algorithms aims to minimize the total power consumption used for sending data to the sink node.

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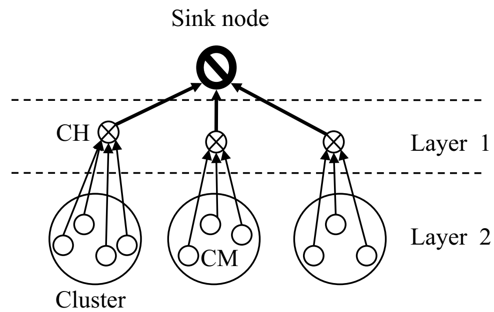


Fig. 2. Hierarchical multi-hop routing.

Fig. 1 illustrates how a flat multi-hop routing algorithm routes data. Each node can communicate with other nodes that are within its maximum transmission range, and an arrow's width is proportional to the amount of data being transmitted between a pair of nodes. The utilization of a single communication link differs with different routing algorithms. For example, algorithms proposed in [5], [6] are designed to minimize the total power consumption of the network. The cost of using a link is defined according to the following equations.

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

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

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

Here, the cost of sending data over from node i to node j, $linkcost(i,j)$, is composed of two parts, cost on sender $e_s(i)$ and the cost on the receiver $r_r(j)$. The term $e_s(i)$ is proportional to the square distance $d_{i,j}$ between node i and node j, while ϵ_1 and ϵ_2 are constants dependent on the sending node's transmission circuit. The term $e_r(j)$ is a constant ϵ_3 dependent on the receiving node's receiving circuit. If the route where the sum of all link costs is minimum is used, the WSN's total power consumption can be minimized, effectively prolonging the lifetime of the network.

While the above algorithm minimizes the total power consumption of the WSN, it overburdens certain nodes, leading to their quick battery exhaustion. To solve this problem, $linkcost$ function is redefined as follows,

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

By dividing $linkcost(i,j)$ by the residual energy of the sending node E_i, the probability of node being chosen decreases as its residual energy decreases. In Toh [7], n is set to be 2, enabling a uniform distribution of power consumption over all nodes and at the same time minimizing the total power consumption of the WSN. Besides the previously mentioned algorithms, others such as zP_{min} [8] and max–min T [9]–[12] have also been proposed.

B. Hierarchical multi-hop routing algorithms

While flat multi-hop routing algorithms successfully route data to minimize the power consumption of the WSN, they fail to take advantage of the nature of data collected by the WSN. The application area and the relatively high node density make the data collected by the WSN highly redundant, thus making data aggregation very attractive in WSNs. Hierarchical multi-hop routing algorithms take advantage of the highly-correlated nature of WSN's collected data, and sensor nodes assume different roles. We describe the most notable example of hierarchical multi-hop routing algorithms, dubbed Low-Energy Adaptive Clustering Hierarchy (LEACH) [13], to illustrate their operation.

LEACH, as illustrated in Fig. 2, is a two-leveled hierarchical routing algorithm in which nodes can take one of two different roles, a Cluster Head (CH) or a Cluster Member (CM), and these roles are changeable in a unit of time referred to as a Round. At the start of every Round, some nodes take the role of CH with a specific probability, and the rest of the nodes become CMs. Each CM chooses a single CH, and a Cluster is formed from a single CH and a few CM(s). Each CM sends its sensed data to its corresponding CH, and each CH aggregates its own sensed data and the data it collected from its CMs, and sends them to the sink node.

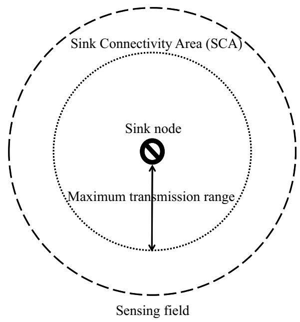
Since CHs in LEACH transmit directly to the sink node and they are relatively small in number than the total number of nodes in the network, the amount of energy consumed tends to become high per single-hop sink node transmission, thus resulting in quick battery drainage of the CHs. Multi-hop variants of LEACH [14], [15] have been proposed, and aim to mitigate this problem by using multi-hop communication between CHs to the sink node.

While CHs are determined randomly in LEACH, changing the principle, which governs how CHs are selected, can decrease power consumption. In HEED [16], a node which has a larger number of links has a higher probability of being chosen as a CH. By doing so, the communication distance between CH and CMs can be decreased, thus resulting in reduction of power consumption in each cluster. On the other hand, in PEACH [17], by increasing the probability of the node with the highest remaining power to become a CH, fairness in power consumption can be improved.

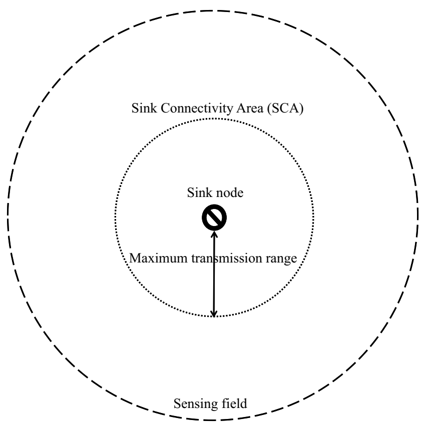
Since the number of nodes used to relay data is relatively small, the transmission distance tends to be large, thus resulting in low-efficiency transmissions. Nevertheless, hierarchical multi-hop routing algorithms are an excellent approach in terms of their ability of capitalizing on the highly correlated nature of data in WSN.

C. Scalability in WSNs

In this section, we present a taxonomy of WSN's structure, to classify the importance of specific nodes over other nodes in the WSN. In wireless multi-hop networks, nodes that lie within the interior of the maximum transmission range of the sink node are provisioned connectivity with the nodes outside its maximum transmission range, through multi-hop transmission, as illustrated in Fig. 3. We refer to this area as Sink Connectivity Area (SCA). As can be observed from Fig. 1, owing to the many-to-one (convergecast) traffic patterns



(a) Small-scale WSN deployment.



(b) Large-scale WSN deployment.

Fig. 3. Sink Connectivity Area (SCA).

in the WSN, the amount of data relayed per node increases as the node's position gets closer to the sink node, in effect, shortening its lifetime. Generally, the nodes in the SCA have much shorter lifetimes than nodes outside the SCA; in the event that all the SCA nodes die, the sink node will become unable to collect data from the WSN, practically making the WSN nonfunctional; we refer to this problem as sink node isolation. As shown in Fig. 3, as the size of the WSN increases, so does the relay load on the sensor nodes, especially on SCA nodes, ultimately shortening the lifetime of the large-scale WSN deployments as compared with small-scale WSN deployments, thus severely limiting the scalability of WSN. In other words, to correctly evaluate the scalability of a WSN routing algorithm, it is essential to take into account the rate in which sink node isolation occurs, while most previous works investigate scalability in terms of total energy consumption or the rate of node's death in the WSN [18]. In this work, we consider the scalability in terms of the rate of sink node isolation with respect to the WSN deployment size. We present our recently proposed algorithm dubbed HYbrid Multi-hop routiNg (HYMN) and show its superior scalability as compared with contemporary WSN multi-hop routing algorithms.

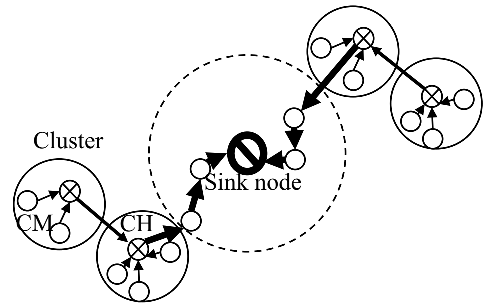


Fig. 4. HYbrid Multi-hop routiNg (HYMN).

III. Hybrid multi-hop routing algorithm

In general, the number of nodes in the SCA is much less than the nodes outside the SCA; inevitability, the volume of data they sense is insignificant as compared with the data they relay. Additionally, while the WSN's size can grow, the SCA's size is constant, implying that to increase the scalability of the WSN with respect to the rate of sink node isolation, the growth rate of flows needs to be limited as the WSN grows in size, and/or the cost of relaying data to the sink node needs to be minimized. Our proposed algorithm HYMN achieves the effect of both solutions by using hierarchical multi-hop routing algorithm to limit the inflow of date from outside the SCA, and using flat multi-hop routing inside the SCA to minimize the transmission distance of nodes inside the SCA.

A. Routing outside the SCA

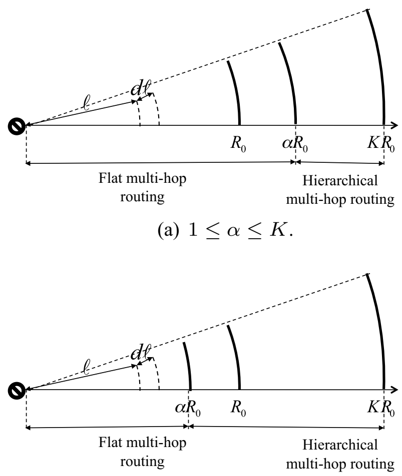
Since transmission power consumption is proportional to the volume of data being relayed in the SCA, limiting the volume of data inflow into the SCA is essential. Applying a hierarchical multi-hop routing algorithm limits the volume of data inflow to the SCA, thus effectively reducing the load on the SCA. This method continues to be effective as the size of the WSN grows, by reducing the volume of data flow.

B. Routing inside the SCA

Inside the SCA, the most important objective of the applied routing algorithm is to minimize the power consumption per transmission while relaying the data flowing in from outside the SCA. This objective can be successfully achieved by applying flat multi-hop routing inside the SCA.

C. Optimal location of hybrid boundary

In this section, we briefly discuss the required size of flat and hierarchical routing algorithms area in order to optimize HYMN, as addressed in [1], in which we defined the concept of hybrid boundary, the location where the employed routing is changed from flat to hierarchical, and vice versa. We introduced the analytical model illustrated in Fig. 5, with its parameters listed in Table I. The problem was divided into two cases, the case where the hybrid boundary is outside the SCA, and that inside the SCA.



(a) $1 \leq \alpha \leq K$.

(b) $0 \leq \alpha \leq 1$.

Fig. 5. Developed mathematical model.

1) The hybrid boundary is outside the SCA: If $1 \leq \alpha \leq K$, as shown in Fig. 5(a), power consumption in the SCA, E^{OUT}, is attributed to two components, 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 was sensed from inside the SCA to the sink node, and that for relaying data flowing into the SCA from outside to the sink node, respectively. E_S^{OUT} and E_R^{OUT} are equal to:

$$E_S^{OUT} = \frac{2}{3}\pi m \rho \frac{e(d_F)}{d_F} R_0^3 \tag{6}$$

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

We inferred from Eq. (7) that E_R^{OUT} is a monotonic increasing function of α, implying that the optimal hybrid boundary lies within the SCA, i.e., $0 \leq \alpha \leq 1$. This result is intuitive in the scene that adopting hierarchical multi-hop routing on all non-SCA nodes would result in the minimum volume of data flowing into the SCA. It is worth noting that this result is independent of the WSN deployment size, KR_0.

2) The hybrid boundary is inside the SCA: If $0 \leq \alpha \leq 1$ as shown in Fig. 5(b), E^{IN}, the energy consumption in the SCA, is attributed to four components, 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 was sensed from inside the interior of αR_0 to the sink node. E_S^{CM} is the energy consumed when CMs send data sensed from the SCA to their respective CHs, and E_S^{CH} is the energy consumed by CHs in the SCA when they send their 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 by both flat multi-hop routing and CH nodes within the SCA. They are equal to:

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 $0 < \gamma \leq 1$

$$E_S^F = \frac{2}{3}\pi m \rho \frac{e(d_F)}{d_F}\alpha^3 R_0^3 \tag{9}$$

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

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

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

E^{IN} can be rewritten in the following polynomial form,

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

where the signs of the coefficients are $A_1 > 0$, $A_2 < 0$, $A_3 < 0$, and $A_4 > 0$. To understand the shape of this function by applying the first derivative test, we have

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

If α is 0, i.e., only hierarchical multi-hop routing is used, $(E^{IN})' = A_3 < 0$ which reflects that the function has a negative gradient; in other words, energy consumption decreases as the hybrid boundary moves away from the sink, and from Eq. (7), we conclude that the optimal hybrid location is inside the SCA. To locate the optimal hybrid boundary, we have conducted computer simulations to measure how the energy consumption of the SCA changes with respect to the hybrid boundary, and our simulation results [1] confirmed our mathematical model. It is interesting to note that the optimal hybrid boundary exists inside the SCA area, and it is intuitive that the optimal hybrid boundary overlaps with the SCA if the compression rate is equal to 1.0, i.e., no data compression. On the other hand, as the compression rate and the CH ratio improve, setting the hybrid boundary inside the SCA can further decrease the energy consumption of the SCA. However, if the size of the hierarchical routing area increases beyond a specific degree, the energy consumption of the SCA starts increasing, owing to undesirable side effects, i.e., the increase in transmission distance inside the SCA.

TABLE II

Configuration of simulation environment.

Parameter	Value
ϵ_1	2×10^{-7} [J/byte/m^2]
ϵ_2, ϵ_3	2×10^{-6} [J/byte/m^2]
Data compression rate	0.8
Probability of node becoming a CH	0.2
Number of nodes	$222 \sim 888$
Field size KR_0	$1000 \sim 2000$ [m]
Maximum transmission range R_0	600 [m]
Data transmission rate m	1 [Byte/round]
Initial energy of each node	10 [J]

D. Effect of WSN deployment size on SCA energy consumption

Herein, we consider the effect of WSN deployment size, KR_0, on energy consumption in the SCA, E_{SCA}, for HYMN as compared with the two conventional categories of WSN multi-hop routing algorithms, i.e., flat and hierarchical. The energy consumption attributed to KR_0 in the case of flat multi-hop routing algorithms, E_{SCA}^{Flat}, can be derived from Eq. (7), with $\alpha = K$, as follows:

$$E_{SCA}^{Flat} = m\pi\rho \frac{e(d_F)}{d_F}(K^2-1)R_0^3. \qquad (15)$$

The energy consumption attributed to KR_0 in the case of hierarchical multi-hop routing algorithms, $E_{SCA}^{Hierarchical}$, can be derived from Eq. (12), with $\alpha = 0$, as follows:

$$E_{SCA}^{Hierarchical} = \gamma m\pi\rho \frac{e(d_{CH})}{d_{CH}}(K^2-1)R_0^3. \qquad (16)$$

The energy consumption attributed to KR_0 in the case of HYMN, E_{SCA}^{HYMN}, can be derived from Eq. (12), with $\alpha = 1$, as the optimal hybrid boundary coincides with the SCA for a large KR_0, as follows,

$$E_{SCA}^{HYMN} = \gamma m\pi\rho \frac{e(d_F)}{d_F}(K^2-1)R_0^3. \qquad (17)$$

From Eq. (2), we can make the following approximation,

$$\frac{e(d)}{d} \cong \epsilon_1 d. \qquad (18)$$

Eqs. (15), (16), and (17) can be rewritten as,

$$E_{SCA}^{Flat} \cong Ad_F(K^2-1) \qquad (19)$$

$$E_{SCA}^{Hierarchical} \cong \gamma Ad_{CH}(K^2-1) \qquad (20)$$

$$E_{SCA}^{HYMN} \cong \gamma Ad_F(K^2-1), \qquad (21)$$

where $A = m\pi\rho\epsilon_1 R_0^3$. As Eqs. (19), (20), and (21) show, the growth of energy consumption in the SCA is proportional to square of the deployment size, K, of the WSN. However, in the case of HYMN and hierarchical multi-hop routing algorithms, data compression, γ, decreases the inflow of data into the SCA. Additionally, the transmission distance in the SCA is an important factor. HYMN successfully utilizes the minimum transmission distance of flat multi-hop routing algorithms, d_F. On the other hand, hierarchical multi-hop routing algorithms suffer from longer transmission distance, d_{CH}. Thus, we conclude from Eqs. (19), (20), and (21) that HYMN has superior scalability. For illustrative purposes, we plot Eqs. (19), (20), and (21), as shown in Fig. 6; d_{CH} and d_F can be estimated from the node density and cluster head ratio by following the parameters listed in Table II. The parameter K is varied to correspond to a field size, KR_0, ranging from 1000m to 2000m.

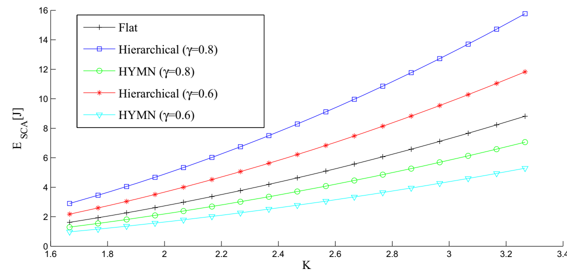


Fig. 6. Effect of WSN deployment size growth on energy consumption in the SCA.

E. Experiment setup

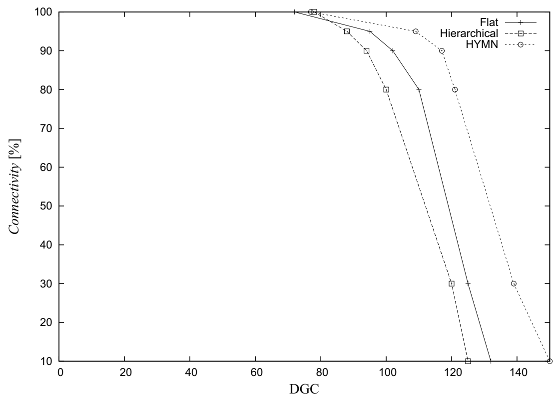
Network Simulator version 2 (NS2) [19] was used to execute our experiments. Sensor nodes are placed in a random uniform manner within a circular sensing field centered on the sink node. Table II shows the configuration of the simulation environment where the value of environmental parameters are set according to the configurations reported in the following references [7], [13]. Since the maximum transmission range of the nodes is 600m, the SCA is also a circular area with a radius of 600m having its center on the sink node. We assume that the nodes are distributed without large deviation in node density, i.e., the number of nodes in the SCA does not deviate much to accurately measure the scalability in our conducted experiments. The experiment is set so that all nodes in the WSN send a single packet in a period of time, referred to as Data Gathering Cycle (DGC), and all packets need to be routed to the sink node. To illustrate the concept of HYMN, Toh's method and a multi-hop variant of LEACH have been employed inside and outside of the SCA, respectively. Also, these two notable multi-hop routing algorithms, as respective representative flat and hierarchical multi-hop routing algorithms, have been used to compare with HYMN.

F. Scalability in terms of sink node isolation rate

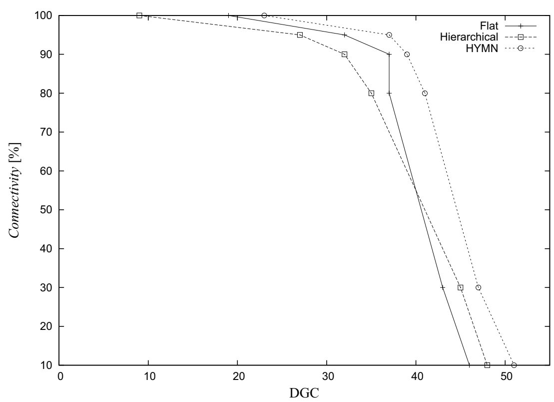
We investigate the scalability of the three categories of WSN multi-hop routing algorithms with respect to sink node isolation rate, i.e., how long can the WSN sustain connectivity before network partition occurs with respect to WSN deployment size, KR_0. As a metric, we use $Connectivity$ to measure the number of DGCs before sink node isolation occurs. $Connectivity$ can be defined as follows,

$$Connectivity = \frac{Number\,of\,Nodes\,Connected\,to\,Sink}{Number\,of\,Nodes}. \qquad (22)$$

Fig. 7 shows two cases of deployment size. It is clear to see the effect of the network size on the scalability of a WSN.



(a) Small-scale WSN ($KR_0 = 1000m$).



(b) Large-scale WSN ($KR_0 = 2000m$).

Fig. 7. Scalability in terms of connectivity.

HYMN successfully sustains $Connectivity$ for the longest period of DGCs as compared to flat and hierarchical multi-hop routing algorithms. As evident from this result, we can conclude that HYMN decreases the rate of sink node isolation, thus improving the scalability of a WSN.

IV. Conclusion

In this paper, we have investigated the scalability limitations in large wireless sensor network deployments. Wireless sensor network routing algorithms can be widely categorized into two categories, flat multi-hop routing algorithms which have an excellent ability in minimizing the total power consumption of the network by using small transmission distances, and hierarchical multi-hop routing algorithms which decrease the volume of data flowing in the network by taking advantage of the highly correlated nature of the collected data by applying data aggregation. In both categories, large-scale deployments have experienced relatively shorter lifetimes as compared to small-scale deployments, because of rapid sink node isolation caused by increased load on nodes within its transmission range, thus limiting the scalability of wireless sensor networks. We show that our recently proposed algorithm, HYMN, successfully improves the scalability of wireless sensor networks. Through mathematical analysis, the relationship between the network size and energy consumption in the SCA has been established. Finally, through extensive simulations, we show that HYMN scales considerably better in terms of network connectivity. The results show that HYMN is promising in terms of its ability to improve the scalability of wireless sensor networks.

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