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Energy-Optimal Grid-Based Clustering in Wireless Microsensor Networks

Yanyan Zhuang, Jianping Pan
Department of Computer Science
University of Victoria
Victoria, British Columbia, Canada
{yyzhuang, pan}@uvic.ca

Guoxing Wu
School of Computer Science
Southeast University
Nanjing, Jiangsu, China
gwu@seu.edu.cn

***Abstract*—Wireless microsensor networks usually consist of a large number of small sensor nodes with limited onboard energy supply and deployed densely in a given area for information harvesting purposes. To reduce energy consumption and prolong network lifetime, clustering techniques are often used, among which the grid-based ones are very popular due to their simplicity and scalability. In this paper, we analyze and evaluate the energy-optimal grid size for a grid-based clustering and routing scheme proposed specifically for wireless microsensor networks. Through numerical and simulation results, we reveal the tradeoff generic to all grid-based clustering schemes. In addition, we propose a randomized technique to further prolong the network lifetime and discuss other energy-saving opportunities. This paper provides some insights into the intrinsic limits of grid-based clustering schemes for wireless microsensor networks.**

***Index Terms*—Wireless microsensor networks, grid-based clustering and routing scheme, energy consumption, network lifetime**

I. INTRODUCTION

Recent technology advancement has made sensor miniaturization possible and affordable for real-world applications. Wireless microsensor networks, with a large number of small sensor nodes, have witnessed an increasing popularity in recent years, and have revolutionized the way how information is collected. Microsensor networks differ from other forms of wireless networks in their limited onboard energy supply and the large volume of data they are expected to convey. Energy conservation therefore is of the primary concern in wireless microsensor networks for typical applications such as environment control and traffic monitoring. Due to this tight energy constraint, one major design challenge in microsensor networks is to reduce the energy consumption, or increase the operational lifetime of a network as much as possible.

By dividing the entire sensor network into small clusters for easy management, and by putting redundant sensor nodes in the same cluster into sleep to save energy, clustering schemes are promising for wireless microsensor networks due to their good scalability and energy conservation potentials. By using geographic coordinates for clustering and routing, grid-based schemes are particularly popular due to their simplicity. In fact, several clustering-based protocols have already been proposed for microsensor networks, such as LEACH [1], TTDD [2], EEDD [3], and our previous work [4].

However, one problem in grid-based clustering is how to determine a *suitable* grid size. Significant energy savings can be achieved when more nodes are put into sleep. Therefore, a larger cluster is preferable if the coverage and connectivity are still maintained. On the other hand, airborne radio transmissions are attenuated by a path loss factor scaling with the distance in a greater-than-linear fashion [5], and the total transmission energy can be reduced by dividing a long-distance transmission into several shorter ones. The problem is how to determine the optimal transmission range or grid size for energy-efficiency, i.e., using the least amount of energy for data transmission while still allowing many nodes to go to sleep. Some work has been done in one-dimension networks, such as [6] and [7], which gives us the inspiration to model and optimize the energy consumption in two-dimension networks. Recent work in two-dimension networks [8] does not consider signal attenuation during wireless transmission. Moreover, it is based on a simple clustering and coordination scheme, which involves a flooding process after each successful grid head re-election. The same problem exists in [9].

A grid-based clustering scheme for two-dimension microsensor networks has been proposed and implemented in our previous work [4]. In this paper, we further model and analyze the energy consumption of this scheme in a more general form, including both the radio and circuit energy consumption. The optimal transmission range and grid size are deduced by using this model, and through both numerical and simulation results, we evaluate better clustering strategies in terms of energy-efficiency and discuss other energy-saving opportunities to further prolong the network lifetime.

The contribution of this paper is the analysis and evaluation of an energy-efficient clustering and routing scheme that totally eliminates the periodic flooding process. By making fewer assumptions on energy consumption and propagation loss models, our work also reveals the energy tradeoff generic to all grid-based clustering schemes, and proposes a randomized technique to further prolong the network lifetime, as well as other energy-saving opportunities. This paper therefore provides some insights into the intrinsic limits of grid-based clustering schemes for wireless microsensor networks, and helps determine a better clustering strategy for energy-efficiency.

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The rest of the paper is organized as follows. We introduce the background and related work in Section II, as well as the problems in grid-based clustering. Section III describes the overall system design. A general modeling of energy consumption, as well as the randomized technique, is given in Section IV, with the aim of achieving the optimal griding. Both numerical and simulation results are presented in Section V, and in Section VI we discuss some further improvements, followed by the conclusions in Section VII.

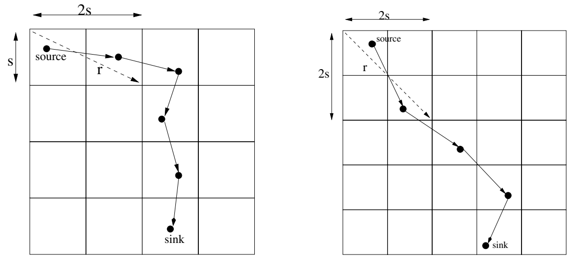
II. BACKGROUND AND RELATED WORK

Clustering schemes that turn off unnecessary nodes within the transmission range of others can be of great benefit for energy conservation. With multi-hop routing, nodes can avoid long-range transmissions, and have no need to be active all the time due to dense deployment. Thus, many clustering schemes have been proposed in various contexts. In [10], the optimal node intensity is determined by Voronoi cells to guarantee a lifetime of at least certain units. Younis *et al.* proposed Hybrid Energy-Efficient Distributed (HEED) clustering [11], which periodically selects cluster-heads according to both their residual energy level and the node proximity to their neighbors. These clustering schemes are heuristic in nature, and demand time synchronization or frequent message exchanges among nodes, which are not ideal in large-scale networks.

Grid-based clustering and routing schemes, in which clusters are equally-sized square grids in a two-dimension plane, have a simple structure with less routing management overhead, and all nodes in one grid are equivalent from the routing perspective. With the assistance of GPS or localization techniques [12], the square grid also provides easier coordination among all sensor nodes in the network. Therefore, it allows for a theoretical analysis while still being useful enough to incorporate all the important elements of a network.

Extensive research work has been done in grid-based clustering. In the early work of GAF [13], the grid size s is chosen such that any two nodes in horizontally or vertically adjacent grids are within the transmission range, r, of each other, which is referred to as Manhattan walk in Fig. 1 (a). By investigating the worst-case scenario, the grid size should be $s \leqslant r/\sqrt{5}$. Recently, the work of [8] also uses this clustering structure. For the one-dimension case [6], s should be less than $r/2$. More recent work of [3] and [4] used a smaller grid size, $s \leqslant r/\sqrt{8}$, allowing nodes in diagonal grids to be in the same transmission range as well, as shown in Fig. 1(b). With the same transmission range r, there are fewer grids in Fig. 1(a), but it may take more hops to reach the sink. Thus the tradeoff between these two griding approaches is still an open question.

In most existing work, energy consumption in electrical circuits has been ignored. Instead, communication-related energy consumption is usually assumed to take a major portion in the total energy consumption. E.g., in [6] the energy consumption other than transmission is assumed to be a constant. This usually leads to a misleading notion that, to minimize energy consumption, it is preferable to send data with more relay nodes to avoid the greater-than-linear path loss penalty due to long-range transmissions. When taking the energy consumption in electrical circuits into account, however, more energy will be used if it takes more hops to reach the destination, and there will be more transmission attempts that lead to higher interference. Thus, there should be an optimal value in the number of transmissions that minimizes the total energy spent in the network, or given a certain node density, the optimal transmission range to prolong network lifetime.



(a) (b)

Fig. 1. Manhattan walk ($s \leqslant r/\sqrt{5}$) and diagonal-first ($s \leqslant r/\sqrt{8}$).

There is some effort in deriving the optimal communication range in one-dimension networks [7], as well as in two-dimension networks [8] and [9]. As mentioned in Section I, the design and analysis in [8] and [9] are quite limited, while [7] studied a simple linear network and deduced the relationship between the optimal radio range and traffic load distribution. This work gave much insight into the relationship between network topology and energy efficiency. The simulation results, however, are obtained by using the Friis free-space model, which is applicable in idealized conditions.

Based on the insights from the linear networks, our work focuses on the two-dimension plane with a grid-based clustering and routing scheme. With fewer assumptions on energy consumption and propagation loss, our work is not merely a simple extension of the literature [7]. By first designing and implementing a multi-hop temperature monitoring system [4], we model the energy consumption in a general form to determine the minimum energy required to bring a unit of data from all nodes to the sink. Given the *working density* of sensor nodes, this model derives the upper and lower bounds of energy consumption in the network, which helps us evaluate better griding strategies and derive the optimal transmission range of sensor nodes in terms of energy-efficiency.

III. SYSTEM DESIGN

There are three modules in the proposed scheme: grid-based clustering, dynamic cluster-head election, and multi-hop routing between clusters [4]. The process of clustering first divides the network into evenly-sized grids, thus provides a location-based clustering topology to other modules. Based on the grid structure, dynamic election rotates the role of a node, either being a cluster-head or a regular working node, according to its current energy level. Multi-hop routing selects a route among these elected cluster-heads, which is also based on the spatially clustered structure. These three models

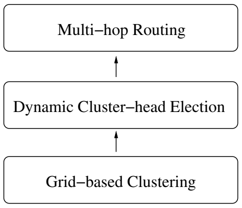


Fig. 2. System design diagram.

therefore constitute the layered structure shown in Fig. 2. With a grid-based scheme, energy can be further conserved by a predefined route between the data source and the sink.

A. Grid Formation

As mentioned in Section II, there are several ways to divide the sensing field into equal-sized grids. Once the grid size s is given, each node calculates its grid coordinate (X, Y) according to the node's location (x, y):

$$X = \lceil x/s \rceil; \;\; Y = \lceil y/s \rceil \tag{1}$$

The $s \leqslant r/\sqrt{8}$ structure in Fig. 1(b) is used for the grid formation in our scheme [4]. The choice between these different structures will be further discussed in Section V with numerical and simulation results. Node location (x, y) can be obtained by GPS devices or localization techniques.

B. Cluster-head Election

Cluster-head election rotates the role of cluster-head among all nodes in a cluster by making constant adaptation to the node energy level. Each time a cluster-head finishes its duty cycle, it retires and the rest of the nodes in the same cluster compete for this position by setting a backoff timer according to their residual energy level. Once the timer fires, the node that first broadcasts a declaration message will become the cluster-head in the next round. This *first-declare-wins* process continues until the energy in all nodes inside the cluster is depleted.

Suppose there are m energy levels in each sensor node. Then nodes in the i-th level (the larger the value of i, the more the residual energy in the battery) set their timer as:

$$t_i = T(i)_{\text{start}} + k \times [T(i)_{\text{end}} - T(i)_{\text{start}}] \tag{2}$$

where $i \in \{1, 2, \ldots, m\}$, and k is a number randomly chosen between $[0, 1]$. $T(i)_{\text{start}}$ and $T(i)_{\text{end}}$ are set such that $T(m)_{\text{start}} < T(m)_{\text{end}} = T(m-1)_{\text{start}} < T(m-1)_{\text{end}} = \ldots = T(1)_{\text{start}} < T(1)_{\text{end}}$, and $T = T(i)_{\text{end}} - T(i)_{\text{start}}$ is a constant. A node with less residual energy has a longer backoff time (as the shaded area in Fig. 3), thus it will be less likely to become the cluster-head in the next duty cycle.

C. Multi-hop Routing

In wireless sensor networks, any node can be a potential data source. The grid structure allows packets to be forwarded in a predefined manner, as shown in Fig. 1. Thus two routing strategies are possible, depending on the griding scheme.

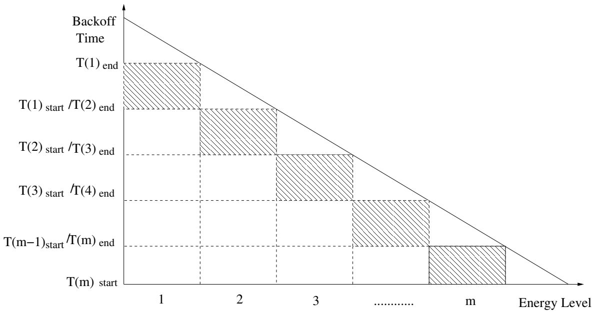
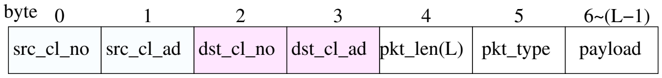


Fig. 3. Energy level vs. backoff time.



byte 0	1	2	3	4	5	6~(L−1)
src_cl_no	src_cl_ad	dst_cl_no	dst_cl_ad	pkt_len(L)	pkt_type	payload

Fig. 4. Packet format [4].

If $s \leqslant r/\sqrt{5}$, packets always go horizontally or vertically until they reach the sink (i.e., Manhattan walk), since the transmission range of a node cannot cover all nodes in its diagonal grids. While if $s \leqslant r/\sqrt{8}$, packets can travel between diagonal grids. Only when packets are forwarded to the same row or column as the sink, will they go horizontally or vertically (i.e., diagonal-first routing). Due to the grid structure, whenever there is data to send, the sender can transmit without the need to set up a route in advance.

D. Packet Design

Figure 4 shows the basic packet format. $\mathrm{cl\_no}$ and $\mathrm{cl\_ad}$ are the identifiers that distinguish a cluster and a node inside the cluster, respectively, just as network and host addresses. $\mathrm{src\_cl\_no}$ and $\mathrm{src\_cl\_ad}$ together identify a source node of a packet, while $\mathrm{dst\_cl\_no}$ and $\mathrm{dst\_cl\_ad}$ identify the next hop. Sink node is a special case of next hop, whose identifier is known by all the other nodes in the network.

Example packet types are listed in Table I. DATA and ACK are typical packets for higher-layer applications; KEEP ALIVE and ELECT are typical control packets. Each active node periodically broadcasts its KEEP ALIVE message that includes its identifier. ELECT is the declaration message that informs the regular working nodes of the new cluster-head. [4] describes the detailed format of data, control and diagnostic packets in our proposed clustering and routing scheme.

TABLE I
PACKET TYPES

Packet Type	Code	Meaning
DATA	$0x01$	sensed data
ACK	$0x02$	acknowledgment
KEEP ALIVE	$0x03$	packet exchange with cluster-head
ELECT	$0x04$	declaration of becoming a cluster-head

IV. SYSTEM MODELING

In this section we model the energy needed for packet transmission and reception, and the optimal grid structure. We assume that there is one sink node in an $L \times L\ m^2$ sensing field, and all other nodes are aware of its location; all nodes use the same transmission range r.

A. Energy Consumption

A general energy consumption model is used here. The transmitter dissipates energy to power up its *e*lectrical circuit, as well as the power *a*mplifier for transmission, i.e., $E^{\text{tx}} = E_e^{\text{tx}} + E_a^{\text{tx}}$. The receiver only needs energy to power the radio electronics, i.e., $E^{\text{rx}} = E_e^{\text{rx}}$ [14]. Energy in electrical circuit, E_e, is determined by the built-in parameters of the microsensors, including factors such as the coding, modulation and filtering of the signal before it is sent to the transmit amplifier, while the communication-related power consumption mainly depends on the environment.

Electrical signals are subject to attenuation once they are sent out by the transmitter. The propagation of electromagnetic waves can be modeled by a decreasing power law function of the distance between the transmitter and receiver, d. If d is smaller than a crossover threshold d_c[1], the propagation loss is proportional to d^2, or d^4 otherwise[2]. Power control, therefore, is used to invert this loss by setting the power amplifier E_a at the transmitter properly to ensure a certain power level at the receiver. Thus, to transmit a b-bit message over a distance d, the energy consumption by the transmitter is[3]

$$E^{\text{tx}}(b,d) = E_e^{\text{tx}}(b) + E_a^{\text{tx}}(b,d) = bE_e + E_a(b,d) \quad (3)$$

$$E_a(b,d) = \begin{cases} b\varepsilon_{\text{Friis}} d^2 & \text{if } d \leqslant d_c \\ b\varepsilon_{\text{two-ray}} d^4 & \text{if } d > d_c. \end{cases} \quad (4)$$

And the energy for receiving a b-bit message is

$$E^{\text{rx}}(b) = E_e^{\text{rx}}(b) = bE_e. \quad (5)$$

If there are n nodes in the sensing area, the *deploying density* P is n/L^2. Since not all sensors in the field are actively sensing, we only need to use a portion of all the nodes for information harvesting. Define ρ as the *working density*, and assume each active node senses one unit of data from the environment in each time slot, the total energy consumption for both cluster-heads and regular working nodes are

$$E_{\text{ch}} = n\rho[2E_e + E_a(d_{\text{int}})] \cdot E[\text{hop}] \quad (6)$$

$$E_{\text{wk}} = n\rho[E_e + E_a(d_{\text{inn}})], \quad (7)$$

where

1) d_{inn} and d_{int} are the distance between active nodes in the same cluster and between neighboring clusters, respectively. d_{inn} and d_{int} thus determine the energy used by the power amplifier.
2) $E[\text{hop}]$ is the average number of hops from any data source to the sink. Given the location of the sink grid (m,n), any data transmission from grid (i,j) following the diagonal-first routing has to go through $H(i,j)_{\text{diag}} = \max\{|i-m|, |j-n|\}$ hops; when the data transmission follows Manhattan walk, $H(i,j)_{\text{Man}} = |i-m| + |j-n|$. Therefore,

$$E[\text{hop}] = \sum_{i,j=0}^{k} H(i,j)/k^2. \quad (8)$$

B. Optimal Griding

From (6)–(8), we can see the relation between the grid size s and the total energy consumption. Whether a grid-based routing scheme can forward data more efficiently depends on the size of the grids in the network and the average number of hops:

$$E_{\text{total}} = n\rho\{[2E_e + E_a(d_{\text{int}})] \cdot E[\text{hop}] + E_e + E_a(d_{\text{inn}})\} \quad (9)$$

Intuitively, sensors can have a shorter transmission range if a smaller grid size is used, so the communication-related power to overcome the propagation loss will be reduced. However, the energy used in radio electronics is increased due to a larger number of transmission and reception attempts. On the other hand, there will be more nodes inside a cluster when using a larger grid size, providing sufficient energy and more forwarding opportunities. But larger grids can also lead to a longer separation between the transmitter and receiver. The tradeoff between picking a small or large grid size to optimize energy consumption is evaluated in Section V with the model calculation and simulation results.

V. PERFORMANCE EVALUATION

Both numerical and simulation results are presented in this section to evaluate the energy-optimal grid size for a grid-based clustering scheme. We first analyze the average number of hops from all data sources to the sink located at any location, and then reveal the performance bounds and the tradeoff generic to all griding schemes. A randomized technique is used to further prolong the network lifetime.

The results in this section are averaged over 80 simulations. Analysis and simulation parameters are given in Table III. All working nodes send data to their cluster-head, while all cluster-heads do data gathering and forwarding at the same time. The time interval during which sensor nodes are sending data depends on application requirements. For the environmental monitoring application in [4], this time interval is set to every 0.8 *sec*. Shorter time interval should be used whenever a smaller initial delay is required by the application.

A. Average Hop Count

$E[\text{hop}]$ and node separation determine the energy spent by all the cluster heads. $E[\text{hop}]$ is, in turn, determined by grid size and sink location. For a sink located at grid (m,n) in the

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[1] d_c is determined by system parameters such as the height of antenna, the wavelength of carrier signal, etc.

[2] d^2 attenuation and d^4 attenuation correspond to Friis free space model and two-ray ground propagation model, respectively.

[3] $\varepsilon_{\text{Friis}}$ and $\varepsilon_{\text{two-ray}}$ depend on the required receiver sensitivity.

TABLE II
u AND v IN EACH BLOCK

Block index (j)	u	v
1	$m-1$	$k-n$
2	$n-1$	$m-1$
3	$k-m$	$n-1$
4	$k-n$	$k-m$

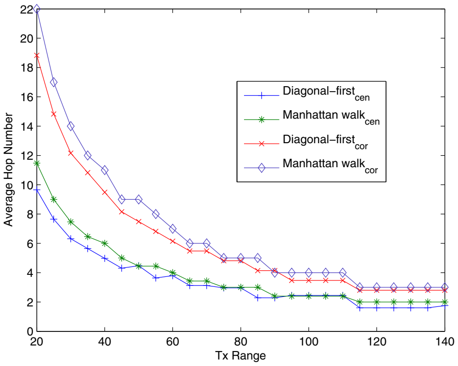


Fig. 5. Average hop count (sensing area 200 × 200 m).

sensing area of $k \times k$ grids, we divide the field into four blocks of $u \times v$ grids each, and obtain the total number of hops in each block as if the sink is at the field corner. First, we define that for each block $j = 1, 2, 3, 4$, we have different values of u and v, as shown in Table II.

In diagonal-first routing, the sum of hops in each block is

$$sum(\text{hop})_j = \sum_{1}^{\min\{u,v\}} i(2i-1) + \min\{u,v\} \times \sum_{\min\{u,v\}+1}^{\max\{u,v\}} i + \sum_{1}^{v} i$$

In Manhattan walk,

$$\begin{aligned} sum(\text{hop})_j = & \sum_{1}^{\min\{u,v\}} i(i-1) + \min\{u,v\} \times \sum_{\min\{u,v\}+1}^{\max\{u,v\}} i \\ & + \sum_{\max\{u,v\}+1}^{u+v} i(u+v+1-i) + \sum_{1}^{v} i \end{aligned}$$

$E[\text{hop}]$ is therefore given by

$$E[\text{hop}] = \frac{1}{k^2} \sum_{j=1}^{4} sum(\text{hop})_j \qquad (10)$$

There are two extreme cases for the average number of hops, i.e., when the sink is in the center of the field (best-case) and in the corner (worst-case). Figure 5 shows these two cases: diagonal-first routing always has fewer hops than Manhattan walk. It is also obvious that in the worst-case, the average number of hops will be much larger.

TABLE III
ANALYSIS AND SIMULATION SETTINGS

Parameter	Meaning	Value
L	length of sensing area	200 m
n	number of nodes	500
ρ	working density	0.5
E_e	electronics energy	50 nJ/bit
ε_{Friis}	Friis-free-space coefficient	10 $pJ/bit/m^2$
$\varepsilon_{two-ray}$	Two-ray-ground coefficient	0.0013 $pJ/bit/m^4$

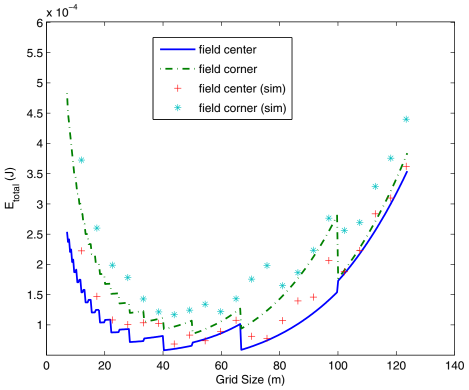


Fig. 6. Energy consumption with diagonal-first routing.

B. Griding Structure and Energy Consumption

In (9), E_{total} is determined by radio electronics, power amplifier and the average number of hops. To gain some insights into how the grid size affects total energy consumption, we use both numerical analysis and simulation to see whether there is an optimal grid size that minimizes E_{total}.

First, solid and dash-dot lines in Fig. 6 are the numerical results in diagonal-first routing, for the lower and upper bounds of total energy consumption. Simulation results are shown in dots. Analytical bounds in Fig. 6 are not smooth because the number of grids is discrete, while the grid size changes continuously. When grid size is around 40 to 50 m, the total energy consumption reaches its lowest level for both the best and worst cases. This corresponds to an energy-optimal transmission range of about 110–130 m. Simulation results show a similar behavior, except they always have a higher energy cost than analytical bounds due to the randomness of the realistic network environment.

Similarly, Fig. 7 shows the results for Manhattan walk. When node transmission range is about 50–60 m, the energy consumption level reaches its minimal level. The optimal transmission range is also 110–130 m due to the same system parameter setting, although the total energy consumed is higher than diagonal-first routing given the same grid size.

Thus, when the grid size is small, data transmission follows the Friis free-space model. Although signal attenuation is not significant, there are more nodes actively working and the average number of hops is larger. With the grid size increasing, some data transmissions are subject to d^4 attenuation, but more redundant nodes can be put to sleep, and less energy is spent in electrical circuitry. At this stage, an optimal grid size is achieved. If the grid continues to grow, the energy

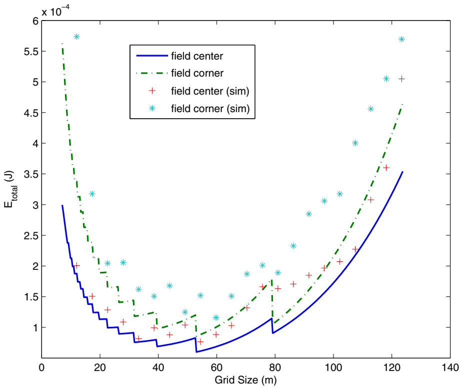


Fig. 7. Energy consumption with Manhattan walk.

consumption associated with transmission increases superlinearly with the radio range, so the total energy consumption grows exponentially with node separation.

Therefore, diagonal-first routing is used in our multi-hop system [4], since it is more energy-efficient for the same parameter setting compared with Manhattan walk. Additionally, data traffic is more balanced due to more freedom of choice in transmission direction. The grid size should be between 40 and 50 m in order to optimize the total energy in the network.

C. Network Lifetime

We define network lifetime as the time when the first grid in the network consumes all the energy of its nodes. Therefore it is determined by the grid that expends the largest amount of energy in the network. In either diagonal-first routing or Manhattan walk, traffic is crowded on the row and column where the sink grid is at (we call this *cross-band*). Manhattan walk suffers more from this uneven distribution of energy because of the limited choices in data forwarding directions. Therefore, we need to make the *cross-band* less crowded with other energy-saving techniques.

The main reason for the relatively crowded area is, in both methods, data traffic is always forwarded to a neighboring grid with the preferred direction, and is eventually routed to the *cross-band*. Thus this area is always crowded with data traffic that is in their final hops. To balance the energy distribution, routing decisions should be less constrained in choosing a forwarding direction. If we choose a direction randomly toward the destination, then the data traffic will be balanced. As a result, the *cross-band* area will be less crowded and the network will have a longer network lifetime.

Figure 8 shows the results of network lifetime with different routing techniques, with the same parameter settings in Section V-B. In most cases, diagonal-first routing is better than Manhattan walk. With randomized routing, the constraint in routing direction is further relaxed. Thus the randomized diagonal-first (DF) routing works even better, although the curve of network lifetime fluctuates irregularly due to randomness. In Fig. 8, the optimal grid size is in the range of 50 m, which conforms to our previous results.

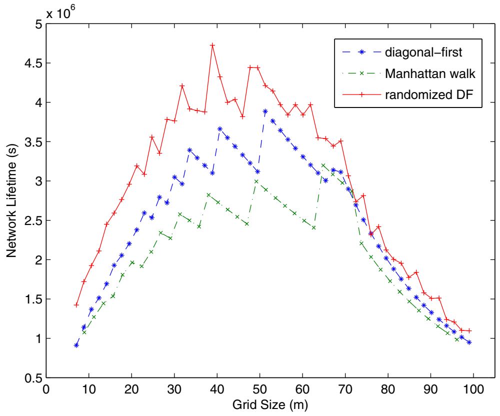


Fig. 8. Network lifetime.

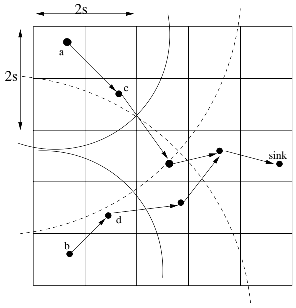


Fig. 9. Concurrent transmission.

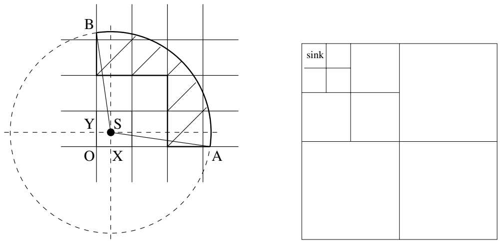
VI. FURTHER DISCUSSION

In this section, we discuss further opportunities for energy-saving in grid-based clustering schemes, which is our focus in the ongoing research and future work.

A. Energy-Throughput Tradeoffs

So far our work has been in the energy domain—the *minimum energy* required to transmit data from all nodes to the sink—but hasn't considered the time, i.e., the *minimum time* to move the same amount of data. This problem is equivalent to maximizing network throughput: the maximum number of concurrent transmissions. Maximizing throughput and lifetime, however, often conflicts with each other. Higher throughput leads to faster energy dissipation, which reduces the network lifetime. In general, to identify the optimal tradeoff between throughput and lifetime is more interesting and practical than optimizing either of them individually.

Transmissions from any node within a given range of the transmitter (referred to as the interference range) will cause a collision and result in packet error. In Fig. 9, transmission on link ac and bd can be scheduled at the same time. Although the interference range of a and b (dashed lines) overlaps, it will not affect destination c and d that are inside the transmission range (solid lines). Therefore, determining the maximum number of concurrent transmissions also depends on the node position and data forwarding direction.



(a) (b)

Fig. 10. Opportunistic forwarding and opportunistic griding.

B. Opportunistic Forwarding and Opportunistic Griding

We assume that nodes are uniformly distributed in all grids. Given the diagonal-first routing, it is guaranteed that one transmission will cover all neighboring grids; however, depending on the location of the cluster-head in the tagged grid, the transmission may reach cluster-heads in some non-neighboring grids in the forwarding direction. Therefore, there is a chance of *opportunistic forwarding*. When the current cluster-head s is in (X, Y), data can be opportunistically forwarded to the stroked area (see Fig. 10(a)). The area of possible opportunistic forwarding is:

$$\begin{aligned} A(x,y) &= \frac{r^2}{2}\left(\frac{\pi}{2} + \arcsin\frac{y}{r} + \arcsin\frac{x}{r}\right) + xy \\ &\quad + \frac{x\sqrt{r^2-x^2}}{2} + \frac{y\sqrt{r^2-y^2}}{2} - 4s^2. \end{aligned} \quad (11)$$

Therefore, with the average cluster-head density of $1/s^2$, the extra opportunistic coverage that a transmission can achieve is:

$$\frac{1}{s^2}\int_0^s \int_0^s A(x,y)dxdy = 5.33s^2. \quad (12)$$

Further, since data traffic is crowded in the area close to the sink, *opportunistic griding* is therefore advantageous in smoothing energy distribution. Grids close to the sink, which have heavy traffic load, will have a smaller size compared with those are farther away. Dividing the network into unequal grids (see Fig. 10(b)) will also lead to different transmission range adjustment in a two-dimension plane.

VII. CONCLUSIONS

In wireless microsensor networks, energy consumption is the most important factor affecting network lifetime. Grid-based clustering organizes sensor nodes into clusters and puts nodes not involved in forwarding into sleep. In this paper, we investigated energy-optimal grid-based clustering for sensor networks by modeling, analysis and simulation. Both analytical and simulation results show that there is an optimal grid size that leads to the minimal energy consumption in a two-dimension sensing field. In addition, randomized and opportunistic techniques can further prolong the network lifetime. Our work provides insights into the intrinsic limits of grid-based clustering schemes, and helps determine a better clustering strategy for energy-efficiency. The discussions in Section VI constitute our ongoing and further work, which will lead to a more in-depth exploration of energy efficiency in wireless microsensor networks.

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REFERENCES

[1] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Hawaii International Conference on System Sciences (HICSS)*, 2000.

[2] H. Luo, F. Ye, J. Cheng, S. Lu, and L. Zhang, "TTDD: Two-tier data dissemination in large-scale wireless sensor networks," *Wireless Networks*, vol. 11, pp. 161–175, 2005.

[3] Z. Zhou, X. Xiang, X. Wang, and J. Pan, "An energy-efficient data-dissemination protocol in wireless sensor networks," in *WOWMOM '06: Proceedings of the 2006 International Symposium on World of Wireless, Mobile and Multimedia Networks*, pp. 13–22, Buffalo, NY, Jun. 2006.

[4] Y. Zhuang, "Research and implementation of energy-aware routing protocol in wireless sensor networks," Master's thesis, Southeast University, Nanjing, China, 2007.

[5] W. B. Heinzelman, A. P. Chandrakasan, and H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks," *Wireless Communications, IEEE Transactions on*, vol. 1, no. 4, pp. 660–670, 2002. [Online]. Available: http://dx.doi.org/10.1109/TWC.2002.804190

[6] P. Cheng, C.-N. Chuah, and X. Liu, "Energy-aware node placement in wireless sensor networks," *IEEE Global Telecommunications Conference, (GLOBECOM'04)*, vol. 5, pp. 3210–3214, Nov. 2004.

[7] Q. Gao, K. J. Blow, D. J. Holding, I. Marshall, and X. H. Peng, "Radio Range Adjustment for Energy Efficient Wireless Sensor Networks," *Ad-Hoc Networks*, pp. 75–82, January 2006. [Online]. Available: http://www.cs.kent.ac.uk/pubs/2006/2194

[8] R. Akl and U. Sawant, "Grid-based coordinated routing in wireless sensor networks," *4th IEEE Consumer Communications and Networking Conference, (CCNC'07)*, pp. 860–864, Jan. 2007.

[9] R. Vidhyapriya and P. T. Vanathi, "Energy efficient grid-based routing in wireless sensor networks," *International Journal of Intelligent Computing and Cybernetics*, vol. 1, no. 2, pp. 301–318, Jan. 2008.

[10] V. Mhatre, C. Rosenberg, D. Kofman, R. Mazumdar and N. Shroff, "A minimum cost heterogeneous sensor network with a lifetime constraint," *IEEE Trans on Mobile Computing*, vol. 4, no. 1, pp. 4–15, 2005.

[11] O. Younis and S. Fahmy, "Distributed clustering in ad-hoc sensor networks: A hybrid, energy-efficient approach," in *Proceedings of IEEE INFOCOM*, pp. 629–640, 2004.

[12] L. Lazos and R. Poovendran, "Serloc: Robust localization for wireless sensor networks," *ACM Trans. Sen. Netw.*, vol. 1, no. 1, pp. 73–100, 2005.

[13] Y. Xu, J. Heidemann, and D. Estrin, "Geography-informed energy conservation for ad hoc routing," in *Proceedings of ACM MobiCom*, pp. 70–84, 2001.

[14] S. Sheng, L. Lynn, J. Peroulas, K. Stone, I. O'Donnell, and R. Brodersen, "A low power CMOS chipset for spread spectrum communications," in *Proceedings of IEEE International Solid-State Circuits Conference*, pp. 346–347, 1996.