Abstract— This paper addresses the issue of the energy-awareness and interference in wireless sensor networks (WSNs). We adopt a 2-dimensional grid clustering mechanism, in which cluster-heads are rotated evenly among all sensor nodes. In addition to transmitting and receiving packets within the electrical and amplification circuit, extra energy is needed in the retransmission of packets due to interference. Our analysis shows that the total energy consumed in the network is directly related to the grid structure, which decides the transmission range based on cluster size. By analysis and simulation, we find that there is an optimal grid structure that balances between energy conservation and interference resolution in wireless sensor networks.

Wireless Sensor Networks, Grid, energy consumption, interference, packet loss

I. INTRODUCTION

Wireless sensor networks (WSNs) with hundreds of tiny nodes, are finding wide applicability and increasing deployment in recent years, as expected. Stochastically distributed in sensor field, large numbers of sensors cooperate with one another through self-organized telecommunication, offering information about remote objects, environmental changes, etc., in unknown or inhospitable terrains. Wireless sensor networks are mainly characterized by their limited and non-replenishable energy supply. Therefore, the main objective of WSN design is to prolong network lifetime by balanced and effective energy consumption.

Clustering is one of the techniques that can extend the lifespan of the whole network, by minimizing the number of nodes that take part in long-distance communication with the sink node, and distributing the energy consumption evenly among all the nodes in the network. Cluster-heads maintain a network backbone for forwarding data packets, while regular nodes routinely monitor any change in the environment. Energy consumption of cluster-heads, however, is much greater than regular nodes, thus requires rotation in the role of cluster-heads among all the nodes, and distributing energy load evenly across the network.

II. RELATED WORK

A. Cluster-based networks

Clustering and partitioning are common techniques used in wireless networks, especially in large-scale multihop environment. Several protocols have been proposed in literature, with the objective of maximizing the sensor network lifetime by adopting cluster-based network architectures. One of the well known clustering protocols is LEACH [1], a cluster-based protocol that includes distributed cluster formation in which the nodes elect themselves as cluster-heads with a predetermined probability. However, LEACH does not guarantee that the desired number of cluster heads is selected and cluster heads are not evenly positioned across the network. A further improvement of this protocol known as LEACH-C is proposed in [2]. In LEACH-C, the cluster formation is done at the beginning of each round using a centralized algorithm by the sink node. The sink uses the information received from each node during the setup phase to find a predetermined number of cluster heads and configures the network into clusters. The cluster groupings are then chosen to minimize the energy required for non-cluster head nodes to transmit their data to their respective cluster heads. Results in [2] have shown that the overall performance of LEACH-C is better than LEACH due to improved cluster formation by the sink node. Moreover, the number of cluster heads in each round of LEACH-C is equal to the desired optimal value. The limitation of both LEACH and LEACH-C is, cluster-heads communicate with sink directly, which is not practical in large networks.

TTDD proposed by Luo et al. [3] provides scalable and efficient data delivery to multiple mobile sinks. Each data source in TTDD proactively builds a grid structure which enables mobile sinks to continuously receive data on the move by flooding queries within a local cell only. It also discussed the cell size $\alpha$, to localize the impact of sink mobility within a single cell. Because the overhead to build a grid decreases while the local query flooding overhead increases as the cell size increases, the total communication overhead is a tradeoff between this two competing components. However, TTDD’s source based grid needs to be changed everytime the target moves, and its target is to handle sink mobility instead of...
energy conservation, the critical problem in wireless sensor networks.

Zhou et al.’s work EEDD [4] provides a comprehensive study of target tracking from grid formation, leader election, sleep scheduling, data dissemination and routing, to target and inquirer mobility. The performance of the proposed system is compared with that of TTDD [3] using simulation. However, the proposed scheme is quite independent of the transmission range of the wireless sensors, which should affect the sleep scheduling and grid structure.

### B. Modeling of Energy Consumption & Wireless Interference

In the wireless world, any wireless signal radiated into space by the transmitter gets subjected to some attenuation over distance, superposed with other wireless signals transmitted in the vicinity. The result is a distorted version of the original signal. For transmission, sending nodes must set their power amplifier to invert propagation loss; on the receiver side, the received signal strength must be strong enough for decoding. Whenever a packet loss occurs, sender would retransmit the packet and thus use more energy.

Modeling energy dissipation and interference is never a trivial task. The received signal is the result of all the simultaneous transmissions in the network, and is decoded by treating the sum of all the other on-going signal transmissions as noise, and extra energy expense is needed to overcome unintended noise.

In this paper, a grid-based clustering mechanism is adopted, in which clusters are equally-sized square grids in a 2-dimensional plane. The intuition behind this mechanism is, when showing a wireless sensor network, we want to depict an area totally covered by radio without any gaps. The square shape lets us more neatly visualize, in theory, how the system is laid out, and it is also easier for coordination among all sensor nodes in the network. This simple structure therefore allows for a theoretical analysis while still being useful enough to incorporate all the important elements such as connectivity and scalability with respect to the size of the network.

We first divide the network topology into equally-sized cluster grids, each with the size of \( s \times s \). For communication of neighboring clusters, we set the cluster size \( s \leq \frac{r}{\sqrt{8}} \), therefore nodes in different clusters can talk to one another in horizontal, vertical and diagonal directions (see Figure 1).

![Grid-cluster Topology](image)

**Fig. 1.** Grid-based Clustering

This is a typical 2-dimensional grid clustering scenario, in which nodes can determine the cluster they belong to according to their geographical location. Apparently, for these grids to communicate with one another, transmission range \( r \) should be larger than \( s \). Our focus is, how large \( r \) should be, or, how the transmission range matters when it comes to the issue of energy efficiency. Many previous works assumed that to minimize the energy consumption, it is better to send data in a multi-hop fashion using relay nodes. But when taking both the energy consumption in transmission and electrical circuit into account, this is not always the case.

Indeed, traffic over multi-hop is preferable in certain scenarios because of the path-loss exponent. From the transmission point of view, \((d_1 + d_2 + \ldots + d_i)^n >> d_1^n + d_2^n + \ldots + d_i^n\). In this multi-hop scenario, however, the energy consumption in the electrical circuit is ignored. Actually, with more hops encountered on the way of packet transmission, more energy will be consumed in transmission and reception electronics, and more energy is needed to overcome contention or interference brought by shorter transmission distance, as well as increased transmitting nodes in the network. When taking all these into consideration in a unified model, there is a tradeoff between energy consumption and number of hops, and there is an optimal transmission range based on grid size in a planar network clustering mechanism.

### III. System Design

#### A. An Overview

We build our system on the grid-based clustering mechanism, with dynamic cluster-head election within each cluster, and multihop routing between clusters – totally three modules for different functional purpose. Cluster-head election changes the role of a node, whether being a cluster-head or a regular working node, based on its current energy level; and the spatially clustered structure allows multihop routing procedure to select a route with only a set of nodes for packet forwarding. With grid structure, energy can be further conserved by a pre-defined route between data source and the sink node, without the need to set up a route in advance.

![Relation between Routing Modules & Phases](image)

**Fig. 2.** Relation between Routing Modules & Phases

#### B. Cluster-head Election

The election algorithm adapts to the node energy level in the network and rotates the role of cluster-head accordingly, with the aim of even energy distribution. Each time a node boots
up, it starts its life cycle either as being a regular working node, or as a cluster-head working with a pre-configured duty cycle. Whenever a cluster-head finishes its duty, it retires and the rest of the nodes in the cluster compete for the cluster-head position. This competition is energy-aware: all the nodes fires a back-off timer according to their current energy remaining in the battery:

\[
t = T_{\text{start}} + k \times (T_{\text{end}} - T_{\text{start}})
\]

Here \( k \) is a random value between \([0, 1]\), so \( t \) is any value that sits between \( T_{\text{start}} \) and \( T_{\text{end}} \). Table 1 shows how the starting and ending time is set – with less residual energy, a node has to wait longer time till its back-off timer expires. Once any timer counts down to 0, the node which first broadcasts a declaration message becomes the cluster-head in the next round. This process depends on local battery information, instead of exchanging control message network wide.

Through our experiment we found, when power voltage becomes lower than 2.2V, the node almost dies. Then it has \( T_{\text{start}} = 5.6\text{ms} \) and \( T_{\text{end}} = 6.6\text{ms} \), the longest back-off time. Thus it would not become cluster-head in the next duty cycle.

### Table I

<table>
<thead>
<tr>
<th>Battery Voltage (V)</th>
<th>( T_{\text{start}} ) (( \mu\text{s} ))</th>
<th>( T_{\text{end}} ) (( \mu\text{s} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v &gt; 3.15 )</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>( 3.00 &lt; v \leq 3.15 )</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td>( 2.70 &lt; v \leq 3.00 )</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td>( 2.50 &lt; v \leq 2.70 )</td>
<td>36</td>
<td>45</td>
</tr>
<tr>
<td>( 2.20 &lt; v \leq 2.50 )</td>
<td>46</td>
<td>55</td>
</tr>
<tr>
<td>( v \leq 2.20 )</td>
<td>56</td>
<td>65</td>
</tr>
</tbody>
</table>

#### C. Multihop Routing

In wireless sensor networks, any node will be the potential data source. Our assumption of network-wide sink location awareness, as well as the good property of grid structure allows packets to be forwarded in a pre-defined manner. Lowest-cost route set-up is never difficult with interest propagation. A straightforward solution is through flooding. It, however, suffers from excessive advertisement that consumes energy quickly. If all nodes broadcast only once, it would both save energy and the time for convergence for the network to operate.

Initially, each node sets its cost to \( \infty \), with \( \gamma \) as the deferral time coefficient. Once a node hears an interest propagation message, it defers its forwarding to a time proportional to the optimal cost to reach the next hop. By setting \( \gamma \) properly (10 according to our experiment), each node broadcasts only once.

1) Initially, the cost at \( X \) is \( L_X \), \( Y \) and \( Z \) are \( \infty \). At time \( t \), \( X \) broadcasts and the message is heard by \( Y \) and \( Z \). \( Y \) sets its cost \( L_Y \) as \( L_X + 2.5 \) where 2.5 is the link cost between \( X \) and \( Y \), and sets its timer to expire after \( \gamma \cdot 2.5 = 25\mu\text{s} \). Similarly, \( Z \) sets its cost as \( L_X + 5 \) and timer as \( 50\mu\text{s} \).
2) At \( t+25 \), \( Y \)’s timer expires. \( Y \) sets \( X \) as its last hop and broadcasts. When \( Z \) hears it, it finds \( L_Z = L_X + 5 > L_Y + 1 \), so it updates cost as \( L_Y + 1 \), and sets timer to expire after \( \gamma \cdot 1 = 10\mu\text{s} \).
3) At \( t+35 \), \( Z \)’s timer expires. \( Z \) sets \( Y \) as its last hop and broadcasts with its minimum cost.

The routing cost on each hop here is defined as the energy for transmission within this hop. Therefore, whenever a node becomes the data source, the packet is sent to its cluster-head, and then it follows this pre-set forwarding process (reversely, from source to the sink node), amongst other cluster-heads, until it reaches the sink node.

### IV. Performance Analysis

In this section we model the energy needed for packet transmission, reception, etc., as well as the extra portion for re-transmission due to interference. By analyzing the read-off between multihop and wireless interference, we have found an optimal transmission range, as well as the grid size for grid-based clustering mechanism.

#### A. Model Background

Our assumptions are as follows. All nodes are homogeneous, have the same transmission range \( r \) and power \( P_I \) for communication, with the same initial energy \( E_0 \). Omnidirectional antenna is used. Sink node is stationary and all other nodes are aware of its location. With ideal physical channel and MAC layer, transmission errors are caused by interference. In a wireless channel, the electromagnetic wave propagation can be modeled as falling off as a power law function of the distance between the transmitter and receiver. No matter which model is used (direct line-of-sight or multi-path fading) [1], the received power decreases as the distance between the transmitter and receiver increases.

Depending on the distance between the transmitter and receiver, either the free space model or the multi-path fading model can be used – if the distance between the transmitter and receiver is less than a certain cross-over distance \( d_c \), then use the Friis free space model (\( d^2 \) attenuation); otherwise use the two-ray ground propagation model (\( d^4 \) attenuation).

According to the radio energy adopted by [1] the transmitter dissipates energy to run the radio electronics and the power amplifier, and the receiver dissipates energy to run the radio...
electronic. Thus, to transmit an l-bit message a distance d, the radio expends:

\[ E_{tx} = E_{tx-e}(l) + E_{tx-amp}(l, d) = l \times E_e + E_{tx-amp}(l, d) \]  

(2)

B. Energy for Transmission and Reception

In electrical operation of wireless sensor nodes, energy consumption is mainly spent in three categories: energy for transmitting/receiving packets, and energy used in the electrical circuit. We can analytically determine energy consumption transmitting/receiving packets, and energy used in the electrical circuit. Thus, to transmit an l-bit message a distance d, the radio expends:

\[ E \]

\( E_{ch} = lE_e + E_{tx-amp}(l, d) \cdot \rho s^2 \)

\[ = [2lE_e + E_{tx-amp}(l, d)] \cdot \rho s^2 \]  

(3)

1 is the number of bits in each data message, and \( d_{int} \) is the distance between the neighboring cluster-heads.

2) Energy consumption of working node. Each working node only needs to transmit its data to the cluster-head. And the energy dissipation is as follows:

\[ E_{wk} = lE_e + E_{tx-amp}(l, d_{inn}) \]  

\[ d_{inn} \] is the average distance from the node to the cluster-head. In general, the sensing area is a \( L \times L \) region and the area occupied by each cluster is approximately \( s^2 \). Therefore, the expected distance raised to the power of \( \alpha \) is given by:

\[ E[d^n] = \int \int [(x_1 - x_2)^2 + (y_1 - y_2)^2]^{\frac{n}{2}} dD_1 dD_2 \]  

\[ |D_1| \cdot |D_2| \]

(5)

Here \( |D_1| \) and \( |D_2| \) are the size of the area where \( (x_1, y_1) \) and \( (x_2, y_2) \) resides. \( \alpha \) can be either 2 or 4, depending on the channel propagation model.

3) Average number of hops. There are approximately \( \frac{L^2}{s^2} \) clusters in the network, and each packet has to traverse \( E[H] \) hops to reach its destination. Without opportunistic routing, packets can only jump between one grid at a time. Then the probability of having a route of length i hops from the sender to the destination is proportional to the number of relay nodes in the area inscribed by two concentric "grid circles" of radii \( s \) and \( s + (i - 1)s \):

\[ p(H = i) = \frac{\rho[(is)^2 - ((i - 1)s)^2]}{\rho L^2} = \frac{s^2(2i - 1)}{L^2} \]  

(6)

As a result, the expected hop count \( E[H] \) is

\[ E[H] = \sum_{i=1}^{L/s} p(H = i) \cdot i = \frac{s^2}{L^2} \sum_{i=1}^{L/s} (2i - 1) \approx \frac{2L}{3s} \]  

(7)

As a comparison, packets jump at most two consecutive grids at a time in opportunistic routing. The average hop count is thus in the order of \( \frac{2L}{3s} \), reducing the number of hops significantly.

4) Putting all together. For all the transmission and reception tasks, the total energy consumed by all the nodes in the network during each time slot is:

\[ E_{tx, wx} = \frac{L^2}{s^2} E_{ch} \cdot E[H] + (\rho L^2 - \frac{L^2}{s^2}) E_{wk} \]  

(8)

That is \( L^2[\rho \cdot \frac{L^2}{s^2}(2E_e + E_{tx-amp}(l, d_{inn})) + (\rho - \frac{1}{\rho})(lE_e + E_{tx-amp}(l, d_{inn})) \] energy consumption in total. Figure 4(a) shows the relation between \( E_{tx, wx} \) and grid size \( s \). There are three cases in which the total energy consumption is affected by node separation: i) both \( d_{inn} \) and \( d_{int} \) are smaller than cross-over distance \( d_c \), following Friis free space model; ii) \( d_{inn} < d_c \) and \( d_{int} > d_c \), communication within cluster follows Friis free space model and communication between neighboring clusters follows two-ray ground model; and iii) both \( d_{inn} \) and \( d_{int} \) become larger than \( d_c \), then following two-ray ground model. As can be seen in Figure 4(a) when \( s = 28m \), \( E_{tx, wx} \) reaches the minimum value. Our assumption of relation between grid size and node transmission range is \( s < \frac{r}{\sqrt{\rho}} \). In Figure 4(b) we show two examples, \( s = \frac{r}{\sqrt{\rho}} \) and \( s = \frac{r}{\sqrt{\rho}} \). If grids are smaller, the overall energy consumption is lower, but larger transmission range is needed to reach the optimal value.

C. Analysis of Interference and Collision

In contrast to energy consumption, which can be determined with accuracy, interference is more random and unpredictable. On the receiver’s side, decoding success is a random event whose probability depends upon the desired signal strength, the level of thermal noise, and the strength of unintended signals from other data sources [7].

Under isotropic path loss, the channel gain from node x to node y is

\[ G(x, y) = \left( \frac{d(x, y)}{d_0} \right)^{-\alpha} \]  

(9)

where \( d(x, y) \) is the distance between x and y, \( d_0 \) is a constant, and \( \alpha \) is the path loss exponent (\( \alpha = 2 \) for free-space...
This time slot. Thus, interference due to data transmissions by other nodes during a single transmission is maintained [10]. Therefore, extra energy should be increased to ensure that the same SINR as with a multiple simultaneous transmissions, the transmitted energy is used to over interference.

### 1) Modeling of interference:

It is assumed that the radio channel is symmetric so that the energy required to transmit a message from node i to node j is the same as energy required to transmit a message from node j to node i for a given signal-to-interference-and-noise-ratio (SINR). When there are multiple simultaneous transmissions, the transmitted energy should be increased to ensure that the same SINR as with a single transmission is maintained [10]. Therefore, extra energy is used to over interference.

Assume \( I_i \) is the total interference at node i in a given time slot. \( I_i \) is the sum of constant thermal noise \( N_i \) and interference due to data transmissions by other nodes during this time slot. Thus,

\[
I_i = P_i = \sum_{j \in (N-i)} P_i \cdot G(j, i) = \sum_{j \in (N-i)} \frac{P_i d_0^\alpha}{d(i,j)^\alpha} \quad (10)
\]

1) Inner-cluster interference. This portion of interference is the current transmission signal received, when one node is scheduled to communicate with the cluster-head inside this cluster. Therefore,

\[
E[\sum_{j \in (N-i)} G(j, i)_{inn}] = \frac{P_i d_0^\alpha}{E[\alpha]} \quad (11)
\]

2) Inter-cluster interference. Totally, in all the remaining \( \frac{L^2}{2} - 1 \) clusters, there is at most one on-going transmission that contribute to inter-cluster interference. Thus

\[
E[\sum_{j \in (N-i)} G(j, i)_{int}] = \frac{P_i d_0^\alpha}{E[\alpha]} \cdot (\frac{L^2}{s^2} - 1) \quad (12)
\]

Therefore the average interference at node i during a time slot is

\[
I_i = P_i d_0^\alpha \cdot \left[ \frac{1}{E[\alpha]} + \frac{1}{E[\alpha]} \cdot (\frac{L^2}{s^2} - 1) \right] \quad (13)
\]

Figure 5 shows the interference level in the above equation we derived.

### 2) Modeling of packet loss probability:

A wireless signal transmission is successful, provided that throughout the duration of the packet transmission \( \frac{P_c}{N + I_{\text{int}}} \geq \beta \), where \( \beta \) is the SINR-threshold at the receiver side [7]. \( P_{ri} \) is the received signal strength, \( N \) is thermal noise and \( E[I_{\text{int}}] \) is the sum of all on-going interference at node i. For a given node, \( P_{ri} \) is the received signal that either comes from a node within the same cluster or in a neighboring cluster, which is predictable. \( N \) is a constant for a given frequency used by transceivers. It is then \( I_{ri} \), the only random value, that contributes to the un-predictableness of SINR.

Many measurements, ranging from psychological to physical phenomena can be approximated, to varying degrees,
by the normal distribution. Assuming that many small, independent transmitting signals are additively contributing to the interference at each independent receiver, the use of the normal model can be theoretically justified by central limit theorem (CLT) [9]. [9] states that the sum of a large number of independent and identically-distributed random variables will be approximately normally distributed if the random variables have a finite variance. Table II shows some sample values of grid size, transmission range, mean and variance of accumulated interference. Variance ranges between 0.11 and 0.36. In Figure 6, there are the corresponding probability density functions (PDF) of these sample value.

<table>
<thead>
<tr>
<th>Grid Size (m)</th>
<th>Tx Range (m)</th>
<th>Mean</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>22.6</td>
<td>-5.46</td>
<td>0.122</td>
</tr>
<tr>
<td>12</td>
<td>33.9</td>
<td>-7.44</td>
<td>0.159</td>
</tr>
<tr>
<td>16</td>
<td>45.3</td>
<td>-8.16</td>
<td>0.206</td>
</tr>
<tr>
<td>20</td>
<td>56.6</td>
<td>-8.75</td>
<td>0.281</td>
</tr>
<tr>
<td>24</td>
<td>67.9</td>
<td>-9.24</td>
<td>0.362</td>
</tr>
<tr>
<td>30</td>
<td>84.9</td>
<td>-9.90</td>
<td>0.271</td>
</tr>
</tbody>
</table>

![PDF of Different Grid Size (Tx range)](image)

Obviously, both the expectation and variance of interference value tend to be smaller if grid becomes larger. Thus longer transmission range will be preferable in the sense of interference. For the estimation of $I_i$ at each node, we therefore model it as a normal random variable as follows. The sum of $\frac{\sum_{j=1,j\neq i}^{N} P_{ji}}{N}$ random interference values is given by $I_i = \sum_{j=1,j\neq i}^{N} P_{ji}(j, i)$, each having finite values of expectation $\mu$ and $\sigma^2$. With [9] we know that $I_i \sim N(\mu, \sigma^2)$. The probability of a successful transmission is therefore,

$$p = Pr(I_i \leq \frac{P_{ri}}{\beta} - N) = \Phi\left[\frac{P_{ri}/\beta - N - \mu}{\sigma}\right]$$

where $\Phi(x)$ is the standard normal CDF.

1) **SINR-threshold.** To determine the value of SINR-threshold according to Shannon’s Theorem [11],

$$C = B \cdot \log_2(1 + SINR)$$

where $C$ is the achievable channel capacity, $B$ is the bandwidth. Our radio energy model assumes 1 Mbps capacity in the transceiver electronics. In the 2.4 GHz band there are 16 ZigBee channels, with each channel requiring 5 MHz of bandwidth. Therefore $\beta$ is 0.149.

2) **Thermal Noise.** This type of noise was first measured by John B. Johnson [12]:

$$N = k_B T \Delta f$$

where $k_B$ is Boltzmann’s constant in joules per kelvin, $T$ is the resistor’s absolute temperature in kelvins, and $\Delta f$ is the bandwidth in hertz over which the noise is measured. The resulting $N$ is the thermal noise power in watts. Plugging in our experimentation parameters, we get the thermal noise at $9.7 \times 10^{-9} mw$, that is -80.1 dBm.

3) **Modeling of energy consumption under possible retransmission:** Now we have successfully modeled the network behavior in terms of energy consumption and interference. Packet loss is the result of significant interference level at the receiver side. To overcome the loss caused by simultaneous transmission, sensors have to retransmit the packet and therefore, spend more energy. Here we model the energy consumption under possible retransmission.

Assuming the re-try limit of each packet transmission is $R_t$, then

$$E_{total} = E_{tx,re} + E_{re,tx}$$

And

$$E_{re,tx} = \sum_{k=1}^{R_t} kE_{tx}(1 - p)^{k-1}p$$

**D. Analysis of Cluster Lifetime**

Here we analyze the behavior of cluster rotation and see how energy is dissipated among all the sensors within a cluster.

First the upper bound of cluster lifetime is achieved if all nodes use their energy in the same manner, the resulting lifetime is therefore

$$T_{ideal} = \frac{nE_0}{E_{total}}$$

where $n$ is the average number of nodes in a cluster. Let $E(t) = \begin{bmatrix} E_1(t) & E_2(t) & \cdots & E_n(t) \end{bmatrix}^T$ denote the residual energy of all the nodes at time slot $t$. $A(t) = \{0, 0, \ldots, 1, \ldots, 0\}$ is the vector which indicate which node is the current cluster-head. We calculate the energy distribution in each time slot $t$:

$$E_i(t+1) = E_i(t) - A_i(t) \cdot E_{ch} - [1 - A_i(t)] \cdot E_{wk}, i = 1, 2, \ldots, n_i$$

Figure 7 and 8 show the results of network lifetime with different routing techniques.
V. 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 conflict 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 a more interesting and practical problem than optimizing either of them individually.

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. 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 will also lead to different transmission range adjustment in a two-dimension plane.

VI. CONCLUSION

In wireless sensor 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. Results show that there is an optimal grid size that leads to the minimal energy consumption in a two-dimension sensing field. Our work provides insights into the intrinsic limits of grid-based clustering schemes, and helps determine a better clustering strategy for energy-efficiency.

REFERENCES


