ECTC: Energy effiCient Topology Control Algorithm for Wireless Sensor Networks

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Abstract

Sensor network which operates on battery are used to gather data in a variety of environments. The data collected by each node is communicated through the network to the sink, which uses all reported data to determine characteristics of the environment or detect an event. Prolonging sensor’s operable lifetime is a main design challenge of these networks. A good energy saving technique in this direction is to schedule nodes’ sleep interval with the communication radio turned off. In this paper, we propose a distributed topology control algorithm, termed ECTC, which uses a clustering approach. It is built on the notion that when a region of a shared channel wireless sensor network has a sufficient density of nodes, significant energy saving is obtained by allowing redundant nodes to sleep. Using the two-hop neighborhood information, certain nodes sequentially select a subset of nodes to be active among all nodes in the neighborhood, to ensure connectivity. Moreover, to ensure fairness, the role of active nodes is rotated periodically to ensure energy-balanced operations. Results from stochastic geometry are used to derive solutions for the values of parameters of our algorithm that minimize the total energy spent in the network when all sensor nodes report data through the cluster heads to the sink.

1. Introduction

The past several years have seen an increasing interest in the development of wireless sensor networks. Such networks could potentially be used for a wide variety of applications. A few possible applications include: monitoring temperature, light and the location of persons in commercial buildings to control the environment in a more energy efficient manner, sensing harmful chemical agents in high traffic areas, monitoring fatigue crack formation on aircraft, monitoring acceleration and pressure in automobile tires [1]. The problem of powering a large number of nodes in a dense network becomes impractical when one considers the prohibitive cost of wiring power to them or replacing batteries. In order for nodes to be conveniently placed and used they must be small, which places a severe limit on their lifetime when powered by a battery. Due to their limited resources, many of the methods developed for the Internet and mobile ad hoc networks cannot be directly applied to sensor networks. An important consideration here is the amount of energy required for sensing, computation and communication. The operable lifetime of a sensor node depends to a large extent on the battery lifetime; hence, it is extremely important to adopt energy-efficient strategies to prolong the network lifetime when the number of sensors is more than necessary. More specifically, if there are redundant sensors, some of them may be scheduled to transit to the power-saving mode. These sensors can be activated later to exchange their role with some active sensors. In such cases, the scheduling should always guarantee the required level of connectivity. Ensuring communication connectivity is essential when scheduling sensors’ on-duty time.

In this paper, we propose a new Energy effiCient topology control algorithm, termed ECTC. The ECTC algorithm increases network lifetime while maintaining connectivity, guaranteeing multi-hop reachability from any source to any destination with a reasonable throughput. Our localized and distributed algorithm is built on the notion that when a region of a shared channel wireless sensor network has a sufficient density of nodes, significant energy saving is obtained by allowing redundant nodes to sleep. Using the two-hop neighborhood information, certain nodes sequentially select a subset of nodes to be active among all nodes in the neighborhood, to ensure connectivity. Moreover, to ensure fairness, the role of active nodes is rotated periodically to ensure energy-balanced operations. A thorough energy analysis is included here to investigate ECTC’s performance, which is derived using a realistic radio energy dissipation model with the aim of minimizing the energy spent in communicating to the sink. We studied the energy saving and how it is affected by factors such as sink placement, radio range and the density of the
network. We used results in stochastic geometry to derive values of parameter for the algorithm that minimize the energy spent in the network of sensor nodes. Another crucial aspect of sensor networks additionally investigated here is their lifetime. These networks should function for a relatively long time, as it may be inconvenient or impossible to recharge or replace node batteries. Thus, we provide an approximate formula to determine the energy savings and network lifetime based on the above energy dissipation model.

The rest of the paper is organized as follows: Section 2 reviews the related work. In Section 3, we describe the ECTC topology control algorithm in details. Later, its energy dissipation is modeled and presented. We discuss the simulation and theoretical results in section 4. Finally, we conclude the paper in section 5.

2. Related Work

Our work has been informed and influenced by a variety of other research efforts. There are various proposals in the area of topology control, mostly validated either using theoretical analysis or simulation, and involve MAC or power control mechanisms. These algorithms deal with limitation of wireless sensor networks, such as energy usage or network capacity, and some provide the theoretical limits and bounds of what is achievable with topology control.

Sparse Topology and Energy Management (STEM) [2] is a topology management technique that trades off power savings versus path setup latency in sensor networks. It emulates a paging channel by having a separate radio operating at a lower duty cycle. Upon receiving a wakeup message, it turns on the primary radio, which takes care of the regular data transmissions. The authors further developed a theoretical model of their system performance. They defined an upper bound for the total energy consumed by a node during a time interval, and the energy savings which can be achieved when employing STEM. Also, they derived the general relationship between the setup latency and the relative energy gain for a node. Adaptive Self-Configuring sEnsor Networks Topology (ASCENT) [3] measures local connectivity based on a neighbor threshold and a packet loss threshold to decide which nodes should join the routing infrastructure based on its application requirements and operational conditions. The authors have conducted comparative performance evaluation of the system with and without ASCENT, and studied the energy savings and delivery rate improvements that can be obtained by using ASCENT. They also built a mathematical model to study the relationship between expected packet delivery and node density.

In SPAN [4], nodes make local decision on whether to sleep or join a forwarding backbone as a coordinator based on connectivity information provided by the routing protocol. SPAN coordinators stay awake and perform multi-hop packet routing within the network, while other nodes remain in power-saving mode, and periodically check if they should switch their roles and become a coordinator. Each node bases its decision on an estimate of how many of its neighbors will benefit from it being awake and the amount of energy available on it. The Geographic Adaptive Fidelity (GAF) [5] scheme has similar goals to SPAN; it conserves energy by identifying redundant nodes and turning their radios off. GAF identifies redundant nodes by their physical location and a conservative estimate of radio range.

In [6], the authors introduced the XTC topology control algorithm. It removes an edge \((u,v)\) if, according to some path-loss model, there is a two-hop path from \(u\) to \(v\) which nevertheless requires less energy than the direct path. For the global case of the network graph being a general weighted graph, XTC computes a resulting subgraph, while maintaining connectivity. The resulting topology features the bounded degree property provided that the neighbor order corresponds to Euclidean distance and the network is a unit disk graph. Also, the authors were able to prove the planarity property for the algorithm. On average-case random unit disk graph, the resulting graph also shows good spanner properties, above all with respect to the energy metric. While XTC fail to prove to have spanner properties on general weighted graph or even on unit disk graph.

Our proposal does not assume the nodes are placed in a two-dimensional surface or the network graph to be a unit disk graph, such as [6]. However, a unit disk graph is impractical, since it assumes the signal attenuation is uniform, which implies that the world is flat and without any obstacles. In realistic sensor networks, nodes are not located in a plane and received signal strength does not solely depends on the distance to the sender [7]. For example, environment factors (e.g. weather and physical obstacles between sender and receiver) can severely affect radio characteristics, causing irregular, non-uniform and dynamic radio propagation patterns at different sensor nodes. We believe that sensor network algorithms should work in a more hostile environment that goes beyond this assumption.

Some other assumptions that are commonly made in the literature are the availability of additional hardware, such as dual radio or double antenna [8] at each node, or exact location information is available by
the mean of GPS, such as GAF [5], which restricting the use of the algorithm. There is also a direct relationship between information quality and energy efficiency of the constructed topology: the more accurate the information available to the nodes, the more energy savings can be achieved [9]. By way of contrast, our proposed algorithm rely on a very low-quality information (merely number and identity of neighbor nodes), and can work on any hardware platform.

The details of the ECTC algorithm are described next, followed by its analysis and its energy dissipation model.

3. The ECTC Algorithm

Our proposed topology control algorithm is motivated by a clustering approach, such as [10]. Clustering the network means that each node is assigned to a cluster of nodes with one master node, which acts as the cluster head (CH). The CH is then responsible for all its assigned nodes and might perform special application tasks, handle data aggregation, control the medium access, or provide routing related functions [11]. After dividing the network into several clusters, ECTC selects some nodes that act as bridges between two or more clusters. In doing so, a connected backbone topology is constructed. Although, such an approach is well known, the contribution of this paper is the efficient selection of CH and bridge nodes in order to save as much energy as possible while still maintaining a connected network. Since ECTC conserves energy by putting redundant nodes to sleep, a major design challenge here is to maintain connectivity in the network. ECTC attempts to select nodes joining the topology to be as sparsely as possible. The operation of ECTC is separated into two phases:

Phase 1: In this phase, ECTC selects a group of active nodes from all nodes in the network to form the forwarding backbone. Active nodes stay awake continuously and perform multi-hop packet routing within the sensor network. Other nodes remain in the power-saving mode, and periodically check if they should wake up and exchange their roles with the active nodes. A node switches state from time to time to ensure that all nodes share the task of providing global connectivity roughly equally. The most crucial aspect of our topology control scheme is the active node selection scheme. Overall, this selection process involves two main parts. The first part concerns with initiating the selection, whereby one or more seed nodes are chosen. The second part involves these nodes to recursively select their one-hop neighbors to cover the entire network, while ensuring redundant nodes are made to sleep. Since ECTC is a distributed scheme, selection needs to be localized.

For the seed node, the sink randomly chooses one of its neighbors to initiate the process. The selection then sequentially progresses in a breadth-first manner toward the rest of the network. The selection of the seed node can depend on its available energy and node degree. A node with more residual energy and higher node degree can be selected as a seed node. To assist in further selection, each node builds its one-hop and two-hop neighbor information. Each seed node then selects a set of nodes from its one-hop neighborhood to serve as bridges. This set of selected neighbor nodes is called its Active list. This set is selected such that the node is able to reach all its two-hop neighbors via the Active list. The Active list of x is then an arbitrary subset of the one-hop neighborhood of x, which satisfies the following condition: every node in the two-hop neighborhood of x must have a path toward x. After that each selected active node selects a subset of its one-hop neighbors to be active. This process repeats at these new active nodes until the network is visited.

Phase 2: After the active nodes (i.e., CH and bridge nodes) are selected, the second phase of the algorithm is to select a number of these active nodes to serve as CHs while the rest act as bridges between two or more CHs. Initially, each active node announces itself as CH. Announcement contention may occur when all active nodes decide to be a CH. ECTC resolves this contention by delaying CH announcements with a randomized backoff delay. Each node chooses a delay value based on its available energy and node degree. A node with more residual energy and higher node degree generates a smaller backoff delay; a node delays its announcement for that amount of time. At the end of the delay, the node broadcasts itself as a CH to its one-hop neighbors. Upon receiving this advertisement, any active nodes (i.e., not yet CH) join the cluster. These non-CH nodes inform the appropriate CHs that they will be members of the cluster. If before the backoff delay time expires, an active node receives a CH announcement message from its one-hop neighbor it cancels its backoff delay
timer and announces itself as a bridge node connecting two or more CHs.

Figure 1 depicts a possible cluster formation for a sample network with six CHs. Each cluster is represented by a circle around the CH that is equal to its radio transmission range. Although some nodes are in more than one cluster, they are assigned to just one cluster. Some of these nodes act as bridges to connect two or more CHs with each other.

In ECTC, a node can be in one of four states: sleep, listen, cluster head and bridge. Initially, all nodes start out in the listen state. When in the listen state, a node turns on its radio and exchanges HELLO messages to gather information about its neighborhood. In addition, when a node enters the listen state, it sets up a timer $T_l$. When $T_l$ expires, if the node did not receive any message from its neighbor nodes, the node enters the cluster head state and sets a timeout value $T_{CH}$. When $T_{CH}$ expires, the node moves to listen state. If before $T_l$ expires, the node receives a WITHDRAW message from its an upstream neighbor, the node turns off its radio and moves into the sleep state, or if the node received a JOIN message, then the node moves into bridge state. This implies that an upstream node has either found the node redundant or is required to be active, respectively. When the node enters the bridge state, it sets a timeout value $T_b$ to determine how long it should stay active. When $T_b$ expires, the node moves back into the listen state. A node in the bridge state periodically checks if it should turn its radio off, and move into the sleep state. This decision is based on the following eligibility rule: it checks whether every pair of its neighbors can reach each other within three-hop. We chose to use three-hop to guarantee a good spanner property, if we use a higher value than three-hops; too many nodes will transit to sleep, and thus two close-by nodes may end up very far in the resulting topology. While, two-hop means only a very limited number of nodes will be eligible to withdraw and this incurs high interference and decreases ECTC ability to conserve energy. A node delays its withdrawal announcement with a randomized backoff delay. When the backoff delay timer expires, the node reassesses its withdrawal eligibility. If the withdrawal is still valid, it announces its withdrawal and transits to the sleep state. When transiting to the sleep state, a node cancels all timers, sets the sleep timer $T_s$ and turns off its radio. A node in the sleep state returns to the listen state after an application dependent sleep time $T_s$. The choice of the timers’ values (i.e., $T_{CH}$, $T_b$ and $T_s$) in ECTC is application preferable and these timers have the same value, Fig. 2 illustrates the application cycle of ECTC. Setting a small value to these timers implies rotating the roles of the nodes often and ensure prolonged network lifetime while causing more packet loss. Packets destined to the active nodes (CH and bridge nodes) may get lost because these nodes transit to sleep state and the routing protocol still consider them as active nodes (traffic forwarder). Thus, if the application requires a high delivery rate we should set a higher value for these timers and reset the sensor nodes less often. This stabilizes the network and improves system performance. In this case we sacrifice the longer network lifetime by better delivery rate.

Since the node has a finite battery capacity, these energy savings (i.e., obtained from turning off the redundant nodes) directly correspond to the same relative increase in the lifetime of a node, which ultimately results in a prolonged lifetime of the sensor network.

3.2. Energy Dissipation Analysis

To determine the optimal parameter for the ECTC algorithm, we make the following assumptions:

- The nodes in the network are distributed uniformly at random as per a homogeneous spatial Poisson process of intensity $\lambda$ in two-dimensional plane [10].
- All nodes are homogeneous and transmit at the same power level; hence, have the same radio range $r$.  

![Figure 1. Built topology with ECTC.](image1)

![Figure 2. The different phases of the network cycle with ECTC.](image2)
• The communication environment is contention and error-free; hence, nodes do not have to retransmit any data.
• The communication from each node follows an isotropic radio propagation model.
• The energy needed for the transmission of one bit of data from node \( u \) to node \( v \) is the same as to transmit from \( v \) to \( u \).
• The sink is located at the corner of the terrain.
• Cluster-heads perform data aggregation.

The overall idea of the derivation of this optimal system parameter -which is the probability of being active (either CH or bridge) \( p \) - value is to define a function for the energy used in the network to disseminate data to the sink. As per the assumptions, the nodes are distributed according to a homogeneous spatial Poisson process. The number of nodes in a square area of side \( M \) is a Poisson random variable, \( N \) with mean \( \lambda A \) where \( A = M \times M \). Let us assume that for a particular realization of the process, there are \( n \) nodes in this area. If a node is required to become a CH, and there are \( p\% \) active nodes as to the total number of nodes, we expect to have \( n p \) nodes elected as CHs and \( (1-p)np \) nodes elected as bridges. Also, the active and redundant nodes are distributed as per independent homogeneous spatial Poisson process \( P_1 \) and \( P_0 \) of intensity \( \lambda_1 = p\lambda \) and \( \lambda_0 = (1-p)\lambda \), respectively.

Using the idea in stochastic geometry, each node joins the cluster of the closest CH to form a Voronoi tessellation [12]. The plane divides into zones called Voronoi cells with each cell corresponding to a P1 process point termed its nucleus. If \( N_i \) is the random variable representing the number of \( P_0 \) process points in each Voronoi cell \( C_i \) and \( L_i \) is the total length of all segments connecting the \( P_0 \) process points to the nucleus in a Voronoi cell, then based on the results in [13]:

\[
E[N_i|N = n] = E[N_0] = \frac{\lambda_0}{\lambda_1} = \frac{1-p}{p} \quad (1)
\]

\[
E[L_i|N = n] \approx E[L_0] = \frac{\lambda_0}{2\lambda_1^2} = \frac{1-p}{2p\tau}\sqrt{\lambda} \quad (2)
\]

Now, to derive the energy dissipation, the free space (\( d^2 \) path loss) channel model is used. According to [10], to transmit an \( l \)-bit packet a distance \( r \) (i.e. its radio range), the radio expends:

\[
E_{Tx}(l, d) = lE_{elec} = l\varepsilon_{fr}r^2 \quad (3)
\]

Where \( E_{elec} \) is the electronic energy that depends on factors like digital coding, modulation, filtering and spreading of the signal and \( \varepsilon_{fr}r^2 \) is the amplifier energy that depends on the distance and the acceptable bit error rate. As to receive a packet, the radio expends:

\[
E_{Rx}(l, d) = lE_{elec} \quad (4)
\]

With ECTC, the dissipated energy by the nodes can be analytically estimated using the computation energy models. Each CH dissipates energy receiving signals from its members, aggregating the signals and transmitting the aggregate signal to the sink. Since a CH could be located at any \((x, y)\) point on the terrain with uniform intensity, the probability density function of its location is constant \((1/M^2)\). The transmission to the sink may also be multi-hop. We could estimate the average distance to the sink \((d_{ToS})\) by integrating the distance function over the area as follows:

\[
E[d_{ToS}] = \iint \sqrt{x^2 + y^2} \cdot \frac{1}{M^2} \, dxdy = \frac{2}{3}M \quad (5)
\]

Limits of the definite integral are \([0, M]\) for both \( x \) and \( y \). If we assume the sink is located at the center of the terrain, range of this integral is changed to \([-M/2, M/2]\] giving \( E[d_{ToS}] = \frac{\sqrt{3}}{6}M \). Accordingly, the average hop to the sink is \( E[d_{ToS}]/r \). Now, let \( C_1 \) represents the energy spent by a CH node during a single round:

\[
E[C_1|N = n] = (E[N_0])lE_{elec} + (E[N_0] + 1)lE_{DA} + \frac{\sqrt{3}}{r}M(2lE_{elec} + l\varepsilon_{fr}r^2) + E_{idle} \quad (6)
\]

We assume lossy data aggregation is performed at the CH with energy for aggregation is \( E_{DA} \). \( E_{idle} \) is the energy spent by the radio while in idle state. Idle state refers to the state when the radio is on but not transmitting or receiving any data.

As for each non-CH node including bridge nodes, it only needs to transmit its data to the CH once during a data interval. Let \( C_2 \) represent the energy used by each non-CH node:

\[
E[C_2|N = n] = lE_{elec} + l\varepsilon_{fr}\left(\frac{E[L_0]}{E[N_0]}\right)^2 \quad (7)
\]

This allows us to determine the energy spent in a cluster \( C_3 \) during each round as:

\[
E[C_3|N = n] = E[C_1|N = n] + E[C_2|N = n] \times E[N_0] \quad (8)
\]

We expect to have \( anp \) clusters in the network, where \( a \) is a fraction of the number of active nodes (CH and bridge nodes). We can now derive the total
energy usage. Let $C$ represent the total energy spent in the system, then:

$$E[C | N = n] = anpE[C_3 | N = n]$$

$$= an\left[2(l-p)E_{elec} + Ea + \frac{\sqrt{2/3}}{r}M(2E_{elec} + e_{fs}r^2) + \frac{e_{fs}(1-p)}{4p\lambda} + (1-\alpha)npE_{idle}\right]$$

The last term represents the energy spent by the radio while in the idle state at the bridge nodes. We expect to have $(1-\alpha)np$ nodes to be Bridges. Removing the conditioning on $N$ yields:

$$E[C] = E[E[C | N = n]]$$

$$= E[N]a\left[2(l-p)E_{elec} + E_{DA} + \frac{\sqrt{2/3}}{r}M(2E_{elec} + e_{fs}r^2) + \frac{e_{fs}(1-p)}{4p\lambda} + (1-\alpha)npE_{idle}\right]$$

$$= a\lambda M^2 \left[2(l-p)E_{elec} + E_{DA} + \frac{\sqrt{2/3}}{r}M(2E_{elec} + e_{fs}r^2) + \frac{e_{fs}(1-p)}{4p\lambda} + (1-\alpha)npE_{idle}\right]$$

The above function gives the total energy used in the network to disseminate data to the sink.

$E[C]$ is minimized by a value of $p$ that is a solution of:

$$\frac{e_{fs}}{4\lambda p^2} + E_{elec} - \frac{\sqrt{2/3}}{r}M(2E_{elec} + e_{fs}r^2) + (1-\alpha)nE_{idle} = 0$$

Equation (11) has two roots where only one is positive. The second derivative of the above equation is also positive for this root, hence minimizing the total energy spent. This only positive root of (11) is given by:

$$p_{opt} = \frac{\ln(\lambda)}{2} \left[\sqrt{\frac{2/3}{r}M(2E_{elec} + e_{fs}r^2) - 2E_{elec} - (1-\alpha)E_{idle}}\right]$$

The above analytical formula enables the computation of the CH probability with ease, which mainly depends on the sensor node density ($\lambda$).

Another crucial metric of a sensor network is the system lifetime. Here, lifetime is defined as the time duration from the instant the network is deployed to the moment when the first sensor node runs out of energy. From (6.10), we can determine the average energy dissipated per sensor in each round of transmission. If each node initially has $B$ joule of battery energy, and there is only one transmission of sensed data to the node’s CH in each round of $t$ period, we could approximate lifetime, $L$ in seconds through:

$$L = \frac{B}{c/n} \times t = \frac{Bnt}{c}$$

Based on this model, an analytical experimentation is performed to obtain a realistic total and average energy dissipated in a sensor network as well as its lifetime, against common network parameters.

4. Results and Discussions

In this section we discuss and analyze the performance of ECTC, using simulation and theoretical results.

4.1. Simulation Results

For these simulation experiments, we assumed that there are 100 sensor nodes distributed uniformly at random in a square $M \times M$ region with $M = 300$ m. The control and data messages are fixed at 64 byte, and sensory data is generated at 10-second interval. Each active node retains its active-status for 300 seconds. Unless otherwise stated, all the following investigations adopt these values as their system parameters as summarized in Table 1. For all simulation results in this chapter, each experiment is repeated 10 times. The performance metrics utilized in our investigations are:

- **Total Energy per round:** This metric represents the energy dissipated by all nodes in a round of data collection.
- **Network lifetime:** This metric represents the time period from the instant network is deployed to the moment when the first node runs out of energy.

To make both the mathematical and simulation results comparable, we did not include the energy cost during the CH and bridge nodes selection phase as well as other layers’ costs (we merely considered the energy consumed by the radio). Figure 3 shows the total consumed energy per round against number of nodes in
the network, mathematical result follows similar pattern as the simulation. As expected, when the number of nodes increases the consumed energy increased. This is because the number of communication in the network increases with the number of nodes.

Table 1. The system parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulator</td>
<td>TOSSIM</td>
</tr>
<tr>
<td>Sensor DATA Timer</td>
<td>10 sec</td>
</tr>
<tr>
<td>MAC-PROTOCOL</td>
<td>B-MAC</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>19.2 kb/s</td>
</tr>
<tr>
<td>Message size</td>
<td>64 bytes</td>
</tr>
<tr>
<td>Terrain, $M \times M$</td>
<td>300 m x 300 m</td>
</tr>
<tr>
<td>Simulation time</td>
<td>10,000 s</td>
</tr>
<tr>
<td>Node radio range</td>
<td>60 m</td>
</tr>
</tbody>
</table>

Figure 3. Total energy dissipated per round against number of nodes through the mathematical (continuous line) and simulation results (dots).

Figure 4. Total energy dissipated against radio range through the mathematical (continuous line) and simulation results (dots). Simulation results plotted on the secondary axis.

In Fig. 4, the impact of the sensor transmission range on the energy dissipation is depicted. There is a rather close match between the mathematical and simulation results. From Fig. 4, it is evident that for a short transmission range, the energy consumption is significantly lower. For example, when comparing the energy consumption for range of 40 to 70 m, there is more energy used in the former for the same monitoring scenario. When the range is increased, the energy usage increased. Even though the average hops between nodes tend to decrease with a longer radio range, the energy usage will be dominated by the higher power required to drive the amplifier rather than the number of transmissions.

From Figs. 3 and 4, it is evident that the mathematical results mainly underestimated the energy usage. This is due to the perfect uniform distribution assumption in this model that may not be achieved in every run of the simulation as well as the difference in the computations.

As such, for these random topologies, the energy consumption is not at the optimal behavior resulting in higher energy estimation in simulation.

4.2. Theoretical Results

This section discusses the experimental results including the description of the chosen parameters set and the adopted sensor network scenario. For these experiments, we assume that there are 100 sensor nodes distributed uniformly in an $M \times M$ region with $M = 100$ m initially. The communication energy parameters are set as: $E_{elec} = 50$ nJ/bit, and $\varepsilon_{fs} = 10$ pJ/bit/m$^2$ and $\varepsilon_{mp} = 0.0013$ pJ/bit /m$^4$. The energy for data aggregation is set as $E_{DA} = 5nJ$/bit per reading [14]. The fraction of CH nodes to the total number of active nodes is set as $\alpha = 50 \%$. The sensor data message size is fixed at 64 bytes. The sink is located at the bottom left corner of the field; any other corner position could be representative for the other corner locations as well. Unless otherwise stated, all the following investigations adopt these values for the system parameters as summarized in Table 2.

Figure 5 shows the total energy spent by the network for different CH probabilities with number of nodes 1000 and 2000. It is observed that all curves depict a higher value of total energy dissipated in the network for very small probability of being active (either CH or bridge). This is due to the presence of small number of CHs with large number of associated sensors to them requiring significant energy expense for data collection from their associates. However, as the CH probability is increased, more CH nodes are likely to be present with smaller number of associates (non-CH). Even though average energy dissipated per CH and its associated nodes reduces, but as more
nodes need to communicate directly with the base station as a higher transmission power, the overall energy dissipation goes higher.

One of the assumptions made for the mathematical analysis was the sink node is located at the corner of the field. To investigate how the sink placement affects the network energy behavior, we repositioned the sink to the center of the field. Figures 6.5 to 6.13 show the impact of the sink placement on the energy dissipation and network lifetime. As expected, the sink location at the center is more energy efficient than the corner location. This is mainly due to the reduced average hops between source nodes and the sink resulting in lower forwarding energy cost. This effect is more pronounced for the corner location.

To see the impact of sensor density on the network energy consumption, we fixed the probability of being active (either CH or bridge) based on $P_{opt}$ obtained using (12). The total energy usage for different sensor density ($\lambda$) is depicted in Fig. 6. It is evident that the total energy dissipated is linearly related to the density. However, these energy values are rather optimistic as we assume the wireless channel is error-free. When the node density is increased, there are more nodes in the same region resulting in higher total energy usage. With more nodes in the network, the second curve in Fig. 6 indicates that the number of CHs also increases albeit very marginally. This observation is consistent with the $P_{opt}$ curve depicted in Fig. 7. It is evident that as the node density is increased, the optimal $P_{opt}$ reduces implying more nodes associating themselves with CHs and thus expending more energy.

To see the impact of sensor density on the network lifetime, it is assumed that each sensor node is initially equipped with 20 J energy, and there is a single transmission in every round of 20 seconds. As shown in Figure 6.8 (a), the node density has a logarithmic effect on network lifetime. Initial increases of the density significantly reduce the network lifetime. This is mainly due to the presence of more nodes associated themselves with the CHs. Thus, any further introduction of nodes into the network has a decreasing rate on the network lifetime. This implies that to deploy nodes in a region, there is a trade-off between the monitoring fidelity and network lifetime expectancy even when the optimal number of CHs is selected.

To see the impact of the probability of being active (either CH or bridge) against network lifetime for different number of nodes, the same setting as above is used. From Fig. 9, it is observed that as the CH probability increased the network lifetime decreases. It can also be observed in Figs. 9 (a) and (b) that placing the sink in the center of the terrain has smaller improvement in the lifetime especially at higher level, consistent with the result reported in Fig. 6.

To investigate the effect of terrain size for a given number of sensor nodes, we assumed that $n$ is 1000 nodes. As expected, Fig. 10 depicts an increase in total energy spent for increasing field area. As the area becomes larger, the node density reduces for a fixed number of nodes. Furthermore, the distance between nodes also increases. Thus, the total energy spent grows significantly. Consistent result is also obtained for the network lifetime as shown in Fig. 11. As more energy is dissipated per round, the overall network lifetime becomes shortened for larger fields.

To see the impact of radio range on network lifetime for a given number of sensor nodes, we assumed that $n$ is 1000 nodes. We fixed the CH probability based on $P_{opt}$ obtained using (12). From Fig. 12, it is evident that the energy savings are higher for networks of sensors with lower communication radius. For two communicating sensor nodes, the energy consumption of their communication grows at least quadratically with their distance [6]. Having one or more relay nodes between them helps to save energy. Therefore, when the radio range is increased, the energy usage increased. Even though the average hops between nodes tend to decrease with a longer radio range, the energy usage will be dominated by the higher power required to derive the amplifier rather that the number of transmissions. Consistent result is also obtained for the network life time as shown in Fig. 13. As more energy is dissipated per round, the overall network lifetime becomes shortened for larger radio range.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field dimension, $M$</td>
<td>100 m</td>
</tr>
<tr>
<td>Message size</td>
<td>64 bytes</td>
</tr>
<tr>
<td>Sensor DATA_Timer</td>
<td>10 sec</td>
</tr>
<tr>
<td>Electronics energy, $E_{elec}$</td>
<td>50 nJ/bit</td>
</tr>
<tr>
<td>Idle energy, $E_{idle}$</td>
<td>0.0105 J/sec</td>
</tr>
<tr>
<td>Amplifier energy, $E_{amp}$</td>
<td>10 pJ/bit/m²</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>0.0013 pJ/bit/m²</td>
</tr>
<tr>
<td>Data aggregation, $E_{DA}$</td>
<td>5 nJ/bit</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>50 %</td>
</tr>
<tr>
<td>Node radio range</td>
<td>60 m</td>
</tr>
</tbody>
</table>

From these results, it is obvious that we are able to accurately quantify the total energy usage as well as network lifetime for various network parameters such as number of CHs, sensor density, radio range, and...
Figure 5. Average energy spent vs. Probability of being active (either CH or bridge) for $n = 1000$ and 2000. In (a) the sink is located at the bottom left corner of the field, where in (b) the sink is located at the center.

Figure 6. Average energy spent and number of CHs vs. sensor density.

Figure 7. $P_{opt}$ vs. sensor density.

Figure 8. Network lifetime and average energy dissipated vs. sensor density for $A = 100$ m$^2$. 

(a) Network lifetime vs. sensor density

(b) Average energy dissipated vs. sensor density.
network area. The analytical equations derived based upon a realistic radio energy dissipation model allow us to determine the optimal CH probability and the corresponding minimal energy level readily. As the number of nodes to be deployed and the chosen region size are within one’s control, the optimal CH probability could be directly configured into the nodes prior to deployment.
5. Conclusion

As energy-awareness is highly critical in the design of sensor networks, we considered the ECTC topology control algorithm that does not require location information a priori. Our goal is minimizing the total energy spent in the network to communicate the information gathered by these sensor nodes to the information-processing center, which is the sink. For this purpose, an analytical model of this algorithm is derived based on the results from stochastic geometry to determine a realistic energy dissipation and network lifetime patterns. We have found the optimal parameter values for this algorithm that minimize the energy spent in the system. It was also found that there is a decreasing improvement on network lifetime, when more nodes are deployed within the same region.

For future work, we plan to implement ECTC on real sensor nodes, and develop an analytical model based on graph theory to prove our algorithm properties, such as connectivity, symmetry, sparseness and bounded degree. As part of our current research, we have assumed that the environment was collision and error free. The integrated use of the message timestamp and a suitable MAC protocol for the creation of collision-free transmission schedule is left for future work.

10. References


