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AN ESTIMATION OF SENSOR ENERGY CONSUMPTION

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Abstract—A comprehensive energy model for wireless sensor networks is provided by considering seven key energy consumption sources some of which are ignored by currently available models. We demonstrate the importance of using such a comprehensive model by comparing it to other existing energy models in terms of the lifetime of a sensor node. We use our model to evaluate energy consumption and node lifetime for a sensor network with fixed configuration and we validate this evaluation by simulation. We show that existing energy models over-estimate life expectancy of a sensor node by 30–58% and also yield an "optimised" number of clusters which is too large. We further make the following two observations: 1) the optimal number of clusters increases with the increase of free space fading energy, 2) for sensor networks with 100 sensors over an area of 10^4–10^5 [m^2], finding the optimal number of clusters becomes less important when free space fading energy is very low (less than 1670 pJ/bit/m^2), while for larger networks, on the other hand, cluster optimization is still important even if free space fading energy is low. Guidelines for efficient and reliable sensor network design as well as extension to a sensor network with rotating cluster heads are provided.

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1. INTRODUCTION

Sensor networks play a major role in many aspects of society including home automation, consumer electronics, military application [1, 2], agriculture, environmental monitoring, health monitoring [3] and geophysical measurement [4]. Usually sensor devices are small and inexpensive, so they can be produced and deployed in large numbers. Their resources of energy, memory, computational speed and bandwidth are severely constrained [5]. Therefore, it is important to design sensor networks aiming to maximize their life expectancy. Different aspects of sensor networks such as data aggregation or fusion [6, 7], packet size optimization [8], target localization [9], design challenges [10], network protocols [11–13] are discussed in the literature with respect to crucial energy limitations and network lifetime maximization [14–18, 20, 21].

Accurate prediction of sensor network lifetime requires an accurate energy consumption model. There have been various attempts to model sensor node energy consumption. We list below several such models and point out certain sources of energy consumption that were not considered in those models.

(i) Heinzelman et al. [11] proposed a model that considers micro-controller processing and radio transmission and receiving only. This model does not consider other important sources of energy consumption, such as transient energy, sensor sensing, sensor logging and actuation.

(ii) The model proposed by Millie and Vaidya [22] does not consider energy consumption of sensor sensing, sensor logging and actuation.

(iii) The Zhu and Papavassiliou's model [15] does not consider energy consumption of transient energy, sensor logging and actuation.

In this paper we provide a comprehensive energy model including certain sources of energy consumption that are not included in previous sensor energy models, i.e., transmit energy, sensor sensing, sensor logging and actuation. This paper also provides guidelines for efficient and reliable sensor network design. In Table 1, we compare these energy models with the new model proposed in this paper.

The paper is organized as follows. In Section 2, we describe our single node energy model and relevant energy consumption sources. In Section 3, we extend our model to a network. We apply our results to a sensor network with fixed configuration. In Section 4 we obtain the optimal number of clusters that maximizes the network lifetime. Section 5 outlines numerical results where we demonstrate the benefit

Table 1. Energy consumption sources considers by various energy models.

Energy Sources	Heinzelman et al. [11]	Millie et al. [22]	Zhu et al. [15]	Our Model
Processing	√	√	√	√
Communication	√	√	√	√
Sensing	–	–	√	√
Transient	–	√	–	√
Logging	–	–	–	√
Actuation	–	–	–	√
Cluster Formation	–	–	–	√

of our comprehensive energy model and its application to a general sensor network with fixed cluster and single-hop transmission. In Section 6 we discuss of applying the proposed energy model to rotation cluster heads or dynamic configuration and Section 7 concludes the paper.

2. SENSOR ENERGY MODEL

We consider a wireless sensor network with a cluster topology, as shown in Fig. 1, in which sensors are grouped into clusters, and

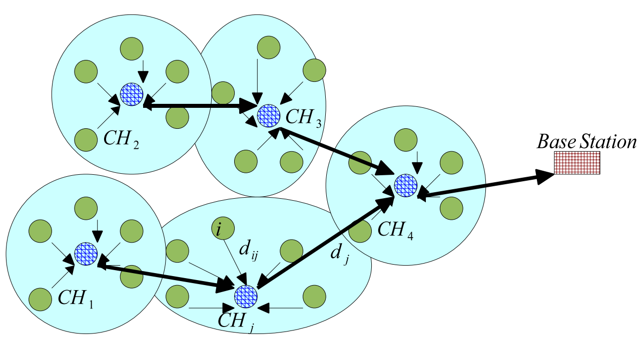

Figure 1. Cluster topology of a Sensor Network: Sensors are grouped into clusters, and individual sensors sense data and transmit to cluster heads (CH). Cluster heads aggregate this data and then forward it through a unique root, depending on the tree structure, to the base station or sink node.

individual sensors sense data and transmit to cluster heads (CH) using single hops as in [11]. Here we assume that all sensor nodes within a cluster use time division multiple access (TDMA) to access their CH. Data is generated in individual sensor nodes. The CH (current CH) processes and aggregates collected data from its own sensors, child CHs (previous CHs) and transmit to its parent CH (next CH) towards to the base station or sink via other CHs with multiple hops. Every communication round base station get equal amount of data. Clustering reduces the data to be transmitted to the base station by processing all data locally. Data aggregation techniques can be used to combine correlated data from sensor nodes into a small set of data which contains only relevant information [11]. Therefore, we assume each sensor senses b bits and transmit to CH. The CH process b_1 bits where $b_1 = b \times$ number of sensors from its own cluster and $\gamma \times b_1$ from child CHs where $\gamma \in 0, 1, 2, \ldots, k-1$ and k is the number of clusters in the sensor network. In general the child CH, in plural: child CHs, would have less data than the parent CH and it all depends on the routing and topology. After processing and aggregation, CH transmits packets with b_2 bits to BS towards parent CH, where $b_2 < b_1 + \gamma \times b_1$.

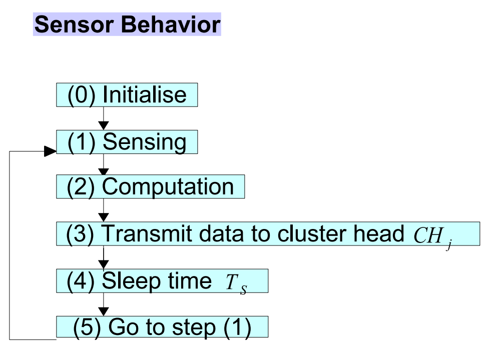

Figure 2. Sensor node operation.

As in [23], a sensor lifetime can be divided into rounds. In each round a sensor node performs steps 1–5 as shown in Fig. 2, and any CH performs steps 1–7 as shown in Fig. 3. We assume that every sensor node generates a fixed-sized packet and forwards to its CH. All generated packets are forwarded to the base station by the CH in each round. The base station schedules transmission time based on time division multiple access (TDMA) to avoid collisions.

In the literature [24], *network lifetime* is defined as either the time until the first (or last) node dies or the time until a given percentage (P_{node}) of the nodes dies. We adopt the latter definition. Note that a node/CH can die either because it runs out of battery, or because the death of other CHs isolates it from its base station. We define C_{opt}, *optimal number of clusters*, as the number of clusters that minimizes energy dissipation. As in [25], we assume a symmetric radio channel making the energy needed to transmit from one point to another in both directions identical. We also assume that all sensors acquire information at a fixed rate, making data available to be sent to the sink every round.

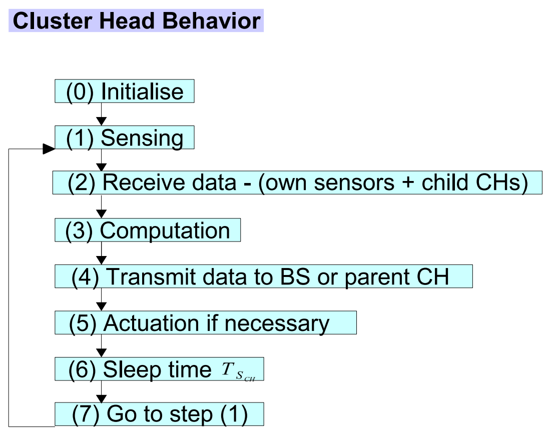

Figure 3. Cluster head operation.

The energy consumed by a sensor node can be attributed to seven main basic energy consumption sources: micro controller processing, radio transmission and receiving, transient energy, sensor sensing, sensor logging and actuation. We assume that all sensor nodes (except CHs) are homogeneous, therefore energy consumption for all activities (excluding for communication energy due to different transmit distances to their CHs), are the same for each sensor node. The total number of data packets (data + control information) in one round is sum of data packets received from the sensor nodes in its own cluster and incoming data packets from child CHs. Therefore, the transmission and receiving energy used by a CH is higher than that of a normal sensor node because of the additional data processing and aggregation tasks associated with it. Let $h_i > 1$ be a weighting factor that applies to a CH to indicate by how much it consumes more energy than a regular sensor node for energy source i, with $i = 1, 2, 3, 4$ for processing, transmission and receiving, sensing and sensor logging, respectively.

The following Sections 2.3 to 2.6 describe the energy needed in each step (Figs. 2 and 3) in detail.

2.1. Sensor Sensing

The sensing system links the sensor node to the physical world. Sources of sensor power consumption are: signal sampling and conversion of physical signals to electrical signals, signal conditioning, and analog to digital conversion (ADC). Let I_{sens} be the total current required for sensing activity and T_{sense} be the time duration for sensor node sensing. We evaluate the total energy dissipation for sensing activity for b bit packet, E_{sens_N} at the sensor node per round by

$$E_{sens_N}(b) = bV_{sup}I_{sens}T_{sens},$$

and the total energy dissipation for sensing activity at the CH per round by

$$E_{sens_{CH}}(h_3, b) = h_3 E_{sens_N}(b).$$

where V_{sup} is the supply voltage.

2.2. Sensor Logging

Sensor logging consumes energy used for reading b bit packet data and writing it into memory [26]. Sensor logging energy consumption for a sensor node per round is evaluated by

$$E_{logg_N}(b) = E_{write} + E_{read} = \frac{bV_{sup}}{8}\left(I_{write}T_{write} + I_{read}T_{read}\right),$$

where E_{write} is energy consumption for writing data, E_{read} is energy consumption for reading b bit packet data, I_{write} and I_{read} are current for writing and reading 1 byte data. Energy consumption for logging sensor readings at the CH per round can be evaluated by

$$E_{logg_{CH}}(h_4, b) = h_4 E_{logg_N}(b).$$

2.3. Micro-controller Processing

The energy for processing and aggregation of the data mainly consumed by the micro-controller, is attributed to two components: energy loss from switching, E_{switch}, and energy loss due to leakage current, E_{leak}.

This energy, dissipated by leakage current, occurs when a subthreshold leakage current flows between the power source and the ground. Total energy dissipation by the sensor node used for data processing/aggregation b bit packet, E_{pro_N}, per round is given by [27]:

$$E_{pro_N}(b_1, N_{cyc}) = \underbrace{b_1 N_{cyc} C_{avg} V_{sup}^2}_{switching} + \underbrace{b_1 V_{sup}\left(I_0 e^{\frac{V_{sup}}{n_p V_t}}\right)\left(\frac{N_{cyc}}{f}\right)}_{leakage},$$

and total energy dissipation by the cluster head (CH), $E_{pro_{CH}}$, per round is given by

$$E_{pro_{CH}}(h_1, b_1, N_{cyc}) = h_1 E_{pro_N}(b_1, N_{cyc}) \qquad (1)$$

where N_{cyc} is the number of clock cycles per task, C_{avg} is the average capacitance switched per cycle, I_0 is the leakage current, n_p is the constant which depends on the processor, V_t is the thermal voltage, and f is sensor frequency. Assuming that sensor nodes only sense data and transmit to their CH once during each round, we ignore energy dissipation due to data processing from regular sensor nodes.

2.4. Radio Transmission and Receiving

Communication of neighboring sensor nodes is enabled by a sensor radio. Energy dissipation by a sensor node can be attributed to transmitting and receiving data. According to [27] the energy dissipation due to transmit b bit packet, in a distance d_{ij} from sensor node to the CH per round is given by

$$E_{tx_N}(b, d_{ij}) = \underbrace{bE_{elec}}_{electronics} + \underbrace{bd_{ij}^n E_{amp}}_{amplifier}, \qquad (2)$$

where E_{elec} is the energy dissipated to transmit or receive electronics, E_{amp} is the energy dissipated by the power amplifier, and n is the distance based path loss exponent (we use $n = 2$ for free space fading†, and $n = 4$ for multi-path fading [28]). Energy dissipation due to receiving b bit packet from the sensor node is given by $E_{rx_N}(b) = bE_{elec}$. Therefore energy dissipation due to transmission of a b_2 bit packet over a distance d_j from the CH to the parent CH per round can be estimated by

$$E_{tx_{CH}}(h_2, b_2, d_j) = h_2 \underbrace{b_2 E_{elec}}_{electronics} + \underbrace{b_2 d_j^n E_{amp}}_{amplifier},$$

where the energy dissipation due to receiving a b bit packet from the CH estimated by $E_{rx_{CH}}(b_2) = h_2 b_2 E_{elec}$.

† Free space fading refers to the attenuation of received signal strength when transmitter and receiver have a clear unobstructed line-of-sight path between them [28].

2.5. Control Packet Overheads

These include energy dissipation from transmitting and receiving RTS, CTS, ACK packets and retransmissions. This is only relevant to contention based protocols like CSMA/CA, not to TDMA which concerns us here.

2.6. Actuation

Energy dissipation for actuation, E_{actu}, is hard to estimate in general because this is highly dependent on application. Total energy dissipation for actuation is $E_{actu}N_{act}$ where N_{act} is the number of actuations per CH. For example if we use temperature sensors to drive a fan that needs two motors, there can be a command to switch on the two motors when temperature is beyond some value and in that case $N_{act} = 2$. In practice, however, actuation may not be performed by any sensor node.

2.7. Transient Energy

Radio and micro-controller units (MCU) support different operating modes including active, idle and sleep. Transitions between operating modes involve significant energy dissipation [22]. Changes in radio operating mode can cause a significant amount of power dissipation. These are often ignored in the literature. Let T_{tranON} and $T_{tranOFF}$ be the times required for sleep-to-idle and idle-to-sleep transitions, respectively. A sensor node will listen to a busy tone of the channel, wake up for a duration of T_A and then sleeps for T_S, assuming $T_S \gg T_A$. Similarly, CH wakes up for duration $T_{A_{CH}}$, which will be discussed in Section 3.2, and then sleeps for $T_{S_{CH}}$. Let T_{tr} be the time between consecutive packet transmissions. The CH will transmit all the packets it receives in one batch every T_{tr} seconds (Fig. 4). This is given by,

$$T_{tr} = T_{A_{CH}} + T_{S_{CH}} = T_A + T_S. \tag{3}$$

The duty cycle for the sensor node, c_N, can be defined as in [22]:

$$c_N = \frac{T_{tranON} + T_A + T_{tranOFF}}{T_{tranON} + T_A + T_{tranOFF} + T_S}.$$

Similarly, the duty cycle for the CH, c_{CH} is defined by:

$$c_{CH} = \frac{T_{tranON} + T_{A_{CH}} + T_{tranOFF}}{T_{tranON} + T_{A_{CH}} + T_{tranOFF} + T_{S_{CH}}}. \tag{4}$$

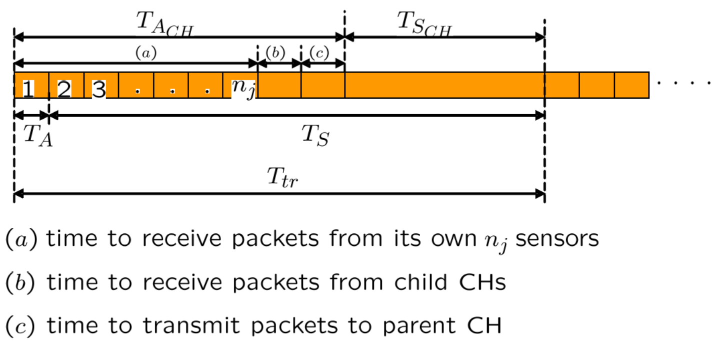

Figure 4. Wake-up and sleeping times of the sensor nodes and the CHs per round.

The average current for a sensor node is given by $I_N = c_N I_A + (1 - c_N) I_S$. The total energy dissipation from the sensor node per round is evaluated by

$$E_{tran_N} = T_A V_{sup} \left[c_N I_A + (1 - c_N) I_S \right],$$

where I_A and I_S are current for active and sleeping mode. Similarly, the average current for a CH is given by $I_{CH} = c_{CH} I_A + (1 - c_{CH}) I_S$ and the energy dissipation due to operating mode at the CH per round is evaluated by

$$E_{tran_{CH}} = T_{A_{CH}} V_{sup} \left[c_{CH} I_A + (1 - c_{CH}) I_S \right].$$

3. NETWORK ENERGY CONSUMPTION

3.1. Applying the Proposed Energy Model to a Fixed Cluster Head

In this section we apply the previously defined energy model to a sensor network, assuming that N_s sensor nodes are randomly and uniformly distributed in a $M \times M$ region.

Consider a k cluster sensor network where the clusters are laid out in a directed tree topology whose root is a base station (sink node). Cluster j comprises one CH denoted CH_j and n_j sensor nodes, $j = 1, 2, \ldots, k$. Thus, on average the number of sensor nodes (including the CH) in a cluster is (N_s/k), as some clusters will have $\lceil N_s/k \rceil$ and some other have $\lfloor N_s/k \rfloor$ sensor nodes.

The total number of sensors is $N_s = \sum_{j=1}^{k} (n_j + 1)$. Sensors transmit information to their respective CH. The CH will then forward the packet through a unique route of CHs to the sink node (the uniqueness results from the tree structure). All transmissions are from the leaves through the intermediate nodes towards the root which is the sink node. Let d_j be the distance between CH_j and the next CH (or the sink node) that it transmits to, and d_{ij} be the distance between node i in cluster j and its cluster head. Here, the total energy consumed by sensor node i in cluster j per round is

$$E_N(ij) = \Bigg[\underbrace{bV_{sup}I_{sens}T_{sens}}_{sensing} + \underbrace{bV_{sup}\left(I_{write}T_{write} + I_{read}T_{read}\right)}_{data-logging} + \underbrace{bE_{elec} + bd_{ij}^{n}E_{amp}}_{transmit} + \underbrace{T_A V_{sup}\left[c_N I_A + (1-c_N)I_S\right]}_{transient}\Bigg]. \quad (5)$$

Similarly, the total energy consumed by cluster CH_j per round is

$$E_{CH}(j) = \Bigg[\underbrace{h_3 bV_{sup}I_{sens}T_{sens}}_{sensing} + \underbrace{h_4 bV_{sup}\left(I_{write}T_{write} + I_{read}T_{read}\right)}_{data-logging} + \underbrace{h_1 b_1 N_{cyc}C_{avg}V_{sup}^2}_{switching}(n_j+1) + \underbrace{h_1 b_1 V_{sup}\left(I_0 e^{\frac{V_{sup}}{n_p V_t}}\right)\left(\frac{N_{cyc}}{f}\right)}_{leakage}(n_j+1) + \underbrace{h_2 b_1 E_{elec}}_{receive-own}(n_j) + \underbrace{h_2 b_2(1+\gamma)E_{elec} + b_2(1+\gamma)d_j^n E_{amp}}_{transmit\ to\ parent\ CH} + \underbrace{h_2\gamma b_2 E_{elec}}_{receive-child\ CH} + \underbrace{T_{CH}V_{sup}\left[c_{CH}I_A + (1-c_{CH})I_S\right]}_{transient} + \underbrace{E_{actu}N_{act}}_{actuation}\Bigg], \quad (6)$$

where $n_j = (N/k), \forall j$, for the case of equi-sized clusters (all clusters have the same number of sensor nodes).

To compute the energy consumption of all $E_N(ij)$ and $E_{CH}(j)$ values, we apply Equations (5) and (6) first to the leaf clusters and recursively progress down the tree until we reach the root.

Therefore the total energy consumed by the entire network per round is given by

$$E_{tot} = \sum_{j=1}^{k}\left(E_{CH}(j) + \sum_{i=1}^{n_j} E_N(ij)\right). \quad (7)$$

3.2. Wake up Time for CH ($T_{A_{CH}}$)

The above energy models require the evaluation of the sensor's duty cycle c_{CH} defined in (4). In this subsection, we derive an expression for CH wake up time, $T_{A_{CH}}$, which is then used to determine c_{CH}.

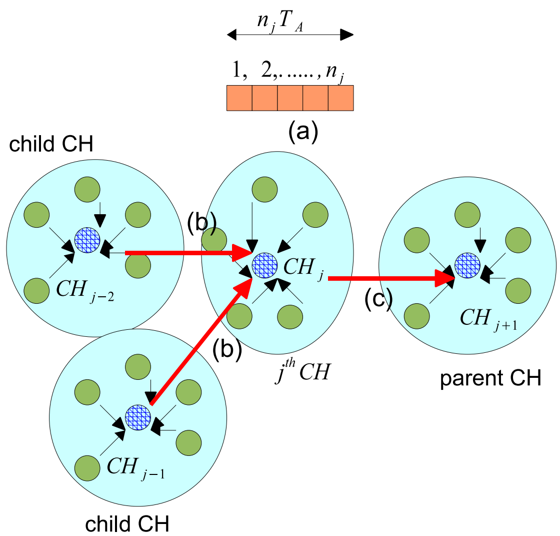

Figure 5. Wake up time for cluster head. This has three components: time taken to receive data from its own sensors, receive data from its child CHs, and transmit data to its parent CH. Data can be received only from child CHs and can be transmitted to their parent CH.

Figure 5 shows an example of a sensor network which we will use to illustrate the data transmission between clusters. With each CH j, we can associate a parent $p(j)$ and a set $c(j)$ of child CHs. A child $c \in c(j)$ is a CH that forwards data to CH j. A parent $p(j)$ is a CH that will transmit data from CH i towards to the base station/sink. For example, in Fig. 5, the parent of CH_j is CH_{j+1} and the child CHs of CH_j is CH_{j-1}, CH_{j-2}, therefore, $c(j) = \{CH_{j-1}, CH_{j-2}\}$ and $p(j) = \{CH_{j+1}\}$.

The total wake up time for jth CH in one round is the total time taken to:

(a) receive data packets from the sensor nodes (total of n_j sensors) in its own cluster, with each sensor having wake up time of T_A,

(b) receive incoming data packets from child CHs and

(c) transmit data packets to its parent CH, $p(j)$.

For a LEACH-type protocol, wake up time for jth CH, $T^j_{A_{CH}}$, is given by:

$$T^j_{A_{CH}} = \underbrace{\max n_j T_A}_{(a)} + \underbrace{\sum_{c\in\ c(j)} T^{CH}_{c,j}}_{(b)} + \underbrace{T^{CH}_{j,p(j)}}_{(c)}, \tag{8}$$

where $T^{CH}_{c,j}$ is the time taken for transmission from its child CH c to CH j, and $T^{CH}_{j,p(j)}$ is the time taken for transmission from CH j to its parent CH $p(j)$. Knowing $T_{A_{CH}}$, the duty cycle of the CH in (4) can be determined.

We find in Sections 3.1 and 6 that the sensor node's energy consumption depends on the number of clusters in a network. In the following we will seek the optimal number of clusters to maximizes the network lifetime.

4. FINDING THE OPTIMAL NUMBER OF CLUSTERS

In this section we apply the principles discussed in the previous sections to develop a technique for increasing network lifetime by choosing the optimal number of clusters. Generally speaking, if we have more clusters while maintaining the same load per CH, the transmission distance from a sensor to its own CH is reduced. Therefore, the overall energy consumption is also reduced. On the other hand, increasing the number of clusters means that the transmission path between a sensor and the BS will include more CH-to-CH hops which means higher overall energy consumption. The aim is therefore to find the optimal number of clusters so that the overall energy consumption is minimized. Note that this optimal clustering depends highly on the energy model used [29]. Therefore, it is important to use the right energy model, as this paper aims to do.

We will now demonstrate the use of our energy model for optimal clustering and compare the results with other approaches. Assume that each sensor node transmits data to its CH only once during each round. Therefore, from (5), total energy consumed by a sensor node during each round is

$$E_{node} = \left[bE_{sens_N} + bE_{logg_N} + bE_{elec} + bd^2_{toCH}E_{fs}\ + E_{tran_N}\right], \tag{9}$$

where b is the number of bits in every packet, d_{toCH} is the distance between node and CH, E_{fs} is the free space fading energy.

Similarly, from (6), the total energy consumed by a CH during each round is

$$\begin{aligned} E_{head} = & \left[bE_{sens_{CH}} + bE_{logg_{CH}} + b_1 E_{pro_{CH}} \left(\frac{N_s}{k} \right) \right. \\ & + h_2 b_1 E_{elec} \left(\frac{N_s}{k} - 1 \right) + h_2 \gamma b_2 E_{elec} + h_2 b_2 (1+\gamma) E_{elec} \\ & \left. + b_2 (1+\gamma) d_{toBS}^4 E_{mp} + E_{tran_{CH}} \right], \end{aligned} \tag{10}$$

where E_{mp} is the multi-path fading energy. Note that we consider a multi path model with d^4 power loss, and assume that actuation is not performed. Consider a square of area $M \times M$ with k clusters, i.e., the area covered by each cluster is approximately M^2/k. As in [11], we assume that the CH is at the center of mass of its cluster, and we acknowledged that the cluster area can be arbitrary shaped, but for simplicity, we assume that it is a square. For $k = 1$, assuming sensors are randomly uniformly distributed over the square area, the mean square distance from a sensor to its CH is given by

$$\begin{aligned} E[d_{toCH}] &= \int_0^M \int_0^M d(x,y) \rho(x,y) dx dy \\ &= \frac{1}{M^2} \int_0^M \int_0^M \left(x - \frac{M}{2} \right)^2 + \left(y - \frac{M}{2} \right)^2 dx dy, \end{aligned} \tag{11}$$

where $\rho(x,y)$, $0 \leq x, y \leq M$, is the joint probability density function. (If sensors are placed uniformly then we have $\rho(x,y) = \frac{1}{M^2}$.)

For $k > 1$, the mean square distance is given by,

$$\begin{aligned} E[d_{toCH}{}^2] &= \frac{k}{M^2} \int_0^{\frac{M}{\sqrt{k}}} \int_0^{\frac{M}{\sqrt{k}}} \left(x - \frac{M}{2\sqrt{k}} \right)^2 + \left(y - \frac{M}{2\sqrt{k}} \right)^2 dx dy, \\ &= \frac{M^2}{6k}. \end{aligned} \tag{12}$$

The above calculation (11) and (12) is for a square area, therefore $k = i^2$ where i is an integer. As an approximation, we evaluate the mean square distance using (11) and (12) with arbitrary value of k. Knowing the mean square distance, we can now derive the optimal number of clusters.

From (9) and (10) the energy dissipation in a single cluster during each round is given by

$$E_{cluster} = E_{head} + \left(\frac{N_s}{k} - 1 \right) E_{node} \approx E_{head} + \left(\frac{N_s}{k} \right) E_{node}. \tag{13}$$

The total energy for k clusters, during each round based on our energy model is obtained using (9), (10), (12) and (13) as

$$\begin{aligned} E_{our} &= kE_{cluster} \\ &= b\,(E_{elec}N_s + E_{pro_{CH}}N_s + d_{toBS}^{n}E_{amp}k + E_{sens_{CH}}k \\ &\quad + E_{tran_{CH}}k + E_{logg_{CH}}k + E_{elec}N_s + E_{fs}\frac{M^2}{6k}N_s \\ &\quad + E_{tran_N}N_s + E_{sens_N}N_s + E_{logg_N}N_s)\,. \end{aligned} \tag{14}$$

We adopt the assumption of [11] that the BS is far from sensor nodes and therefore the distance between CH to the BS for all CHs be considered to be equal. By differentiating (14) with respect to k and equating to zero, the resulting optimal number of clusters, C_{opt}, is

$$C_{opt} = \left\lceil \frac{\sqrt{N_s}}{\sqrt{6}} \frac{M}{d_{toBS}^2} \sqrt{\frac{E_{fs}}{D_\alpha}} \right\rceil, \tag{15}$$

where $D_\alpha = (E_{mp} + E_{sens_{CH}} + E_{tran_{CH}} + E_{logg_{CH}})$. Knowing C_{opt}, for a given network, we can evaluate the average radius of a circular cluster as $M/\sqrt{\pi C_{opt}}$, the average length of square cluster as $M/\sqrt{C_{opt}}$, and the circum radius of the hexagon is $\sqrt[4]{\frac{4}{27}}M/\sqrt{C_{opt}}$. Providing these cluster shape alternatives allows designers to choose the one appropriate for their work. Once we have found the optimal number of clusters, we can calculate the network energy and compare it with results obtained by other energy models. According to Heinzelman et al. [11], the total energy during each round, E_{Hein}, is given by

$$\begin{aligned} E_{Hein} &= b\Big(E_{elec}N_s + E_{pro_{CH}}N_s + d_{toBS}^4 E_{mp}k \\ &\quad + E_{elec}N_s + E_{fs}\frac{1}{2\pi}\frac{M^2}{k}\Big). \end{aligned} \tag{16}$$

In the following we compare the average energy dissipation of our energy model and that of other energy models in [11, 15, 22].

In Fig. 6 and Table 2, we show that in our proposed energy model, the range of the optimal number of clusters is $1 < C_{opt} < 6$, while according to the energy models in [11, 15, 22], the range is within $2 < C_{opt} < 16$, when the distance between the CH and the sink node is between 45–145 m. Our simulation results agree with this analysis and will be discussed more details in Section 5. For example, for a distance of 55 m, the over-estimation of the optimal number of clusters is 194.15% [11], 101.62% [22], and 74.06% [15]. This shows the difference between the models. Nevertheless, the difference in optimal number of clusters between these energy models is getting closer as the distance between the sink and the CHs increases, as shown in Fig. 6. This is because, as this distance increases the energy dissipation for communication becomes more and more dominant in the cost function.

An optimal number of clusters for a given number of sensors is found by varying the distance and comparing the energy dissipation per round. From the simulation results, it is confirmed that the optimal number of clusters is three for [11], two for [22] and [15], and one for

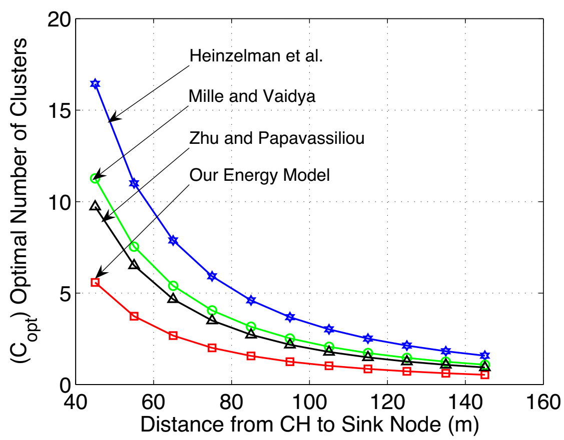

Figure 6. Optimal number of clusters with distance from CHs to sink node or base station — Analytical results for $N_s = 100$ nodes, $M = 100$, $E_{fs} = 7\,\text{nJ/bit/m}^2$ and $E_{mp} = 0.0013\,\text{pJ/bit/m}^4$ when $45 <$ distance < 145 is maintained.

Table 2. Optimal number of clusters with different energy models, for $N_s = 100$ sensor nodes and $M = 100$, when the distance between the CH and the sink node is between 45–145 m.

Energy Model	$E_{fs} = 7$ [nJ/bit/m^2] C_{opt} Range $45 < d_{toBS} < 145$	$E_{fs} = 7$ [nJ/bit/m^2] C_{opt} Simu.	$E_{fs} = 10$ [pJ/bit/m^2] C_{opt} Range $45 < d_{toBS} < 145$	$E_{fs} = 10$ [pJ/bit/m^2] C_{opt} Simu.
Our Model	1-6	3	0-2	1
Zhu et al.	1-12	5	0-4	2
Mille et al.	2-13	6	0-5	2
Heinz. et al.	2-16	11	1-7	3

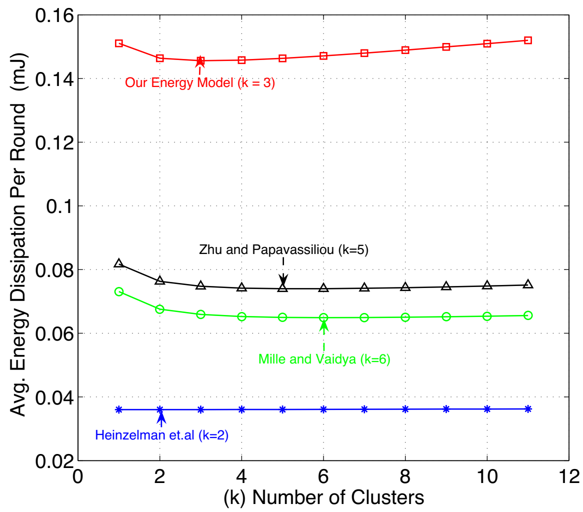

Figure 7. Average energy dissipation versus number of clusters when $E_{fs} = 7\,\mathrm{nJ/bit/m^2}$ and $N_s = 100$ nodes, $M = 100$ by using (13). Optimal number of clusters, based on their energy models, are indicated with arrows. Here the average distance from CH to base station or sink node is 22 m. This shows the difference between the energy models does have significant effect to the sensor energy dissipation. Observe the difference is about 8 pJ per round.

our energy model when $E_{fs} = 10\,\mathrm{pJ/bit/m^2}$ with 100 node network. Therefore, we can conclude that clustering will not increase efficiency when the deployment area is small.

Figure 7 shows the average energy dissipation versus number of clusters when $E_{fs} = 7\,\mathrm{nJ/bit/m^2}$ and $N_s = 100$ nodes, $M = 100$ using (13). The optimal number of clusters, based on different energy models, are indicated with arrows. According to Fig. 7, optimizing the number of clusters does have significant effect on sensor network lifetime. We also observe that the optimal number of clusters of our energy model is three while the energy models of [11, 15] and [22] will lead to optimal number of clusters to be 2, 5, and 6, respectively, for the same free space fading energy. The main reasons for this variation lie in our use of a more comprehensive energy model with a more realistic estimation of processing energy which turned out to be higher than the value considered in [11, 15, 22].

From Figs. 8–11, we can observe that: 1) the number of clusters varies with the energy model used, as well as the distance from the CH to the base station, 2) energy dissipation varies with the number

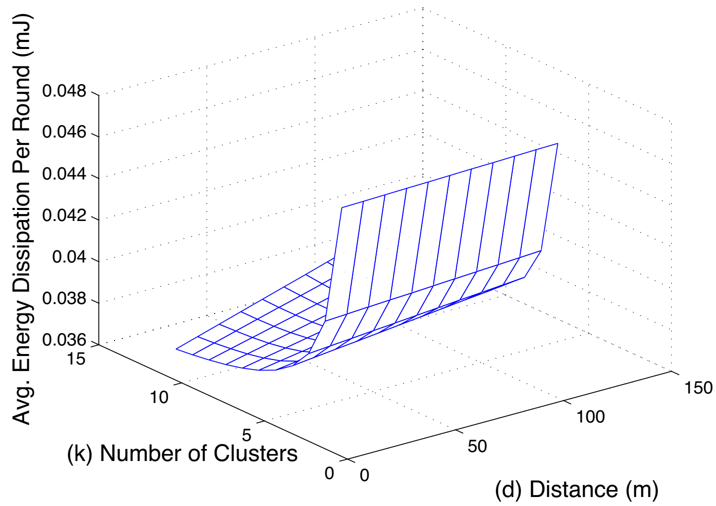

Figure 8. Average energy dissipation versus no. of clusters and distance for Heinzelman et al. energy model. Distance with $N_s = 100$ nodes, $M = 100$, $E_{fs} = 7\,\mathrm{nJ/bit/m^2}$ and $E_{mp} = 0.0013\,\mathrm{pJ/bit/m^4}$.

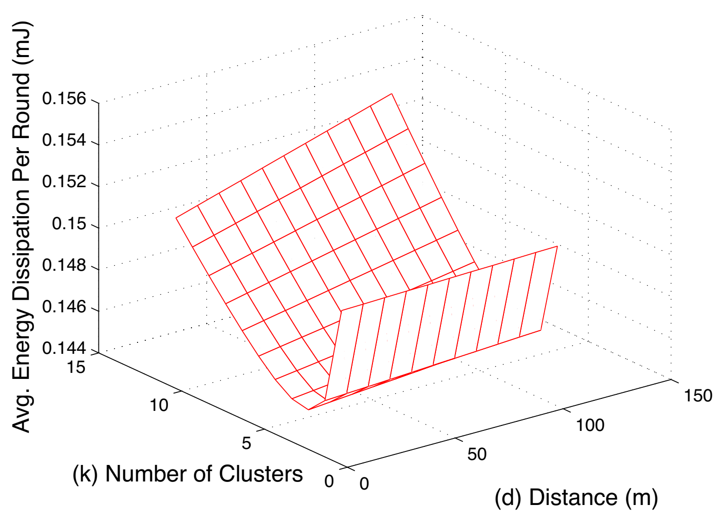

Figure 9. Average energy dissipation versus no. of clusters and distance for our energy model. Distance with $N_s = 100$ nodes, $M = 100$, $E_{fs} = 7\,\mathrm{nJ/bit/m^2}$ and $E_{mp} = 0.0013\,\mathrm{pJ/bit/m^4}$.

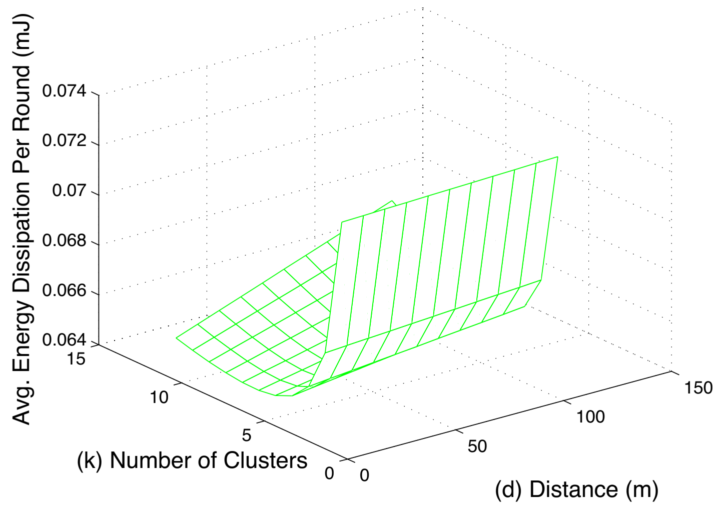

Figure 10. Average energy dissipation versus no. of clusters an distance for Mille and Vaidya energy model. Distance with $N_s = 100$ nodes, $M = 100$, $E_{fs} = 7\,\mathrm{nJ/bit/m^2}$ and $E_{mp} = 0.0013\,\mathrm{pJ/bit/m^4}$.

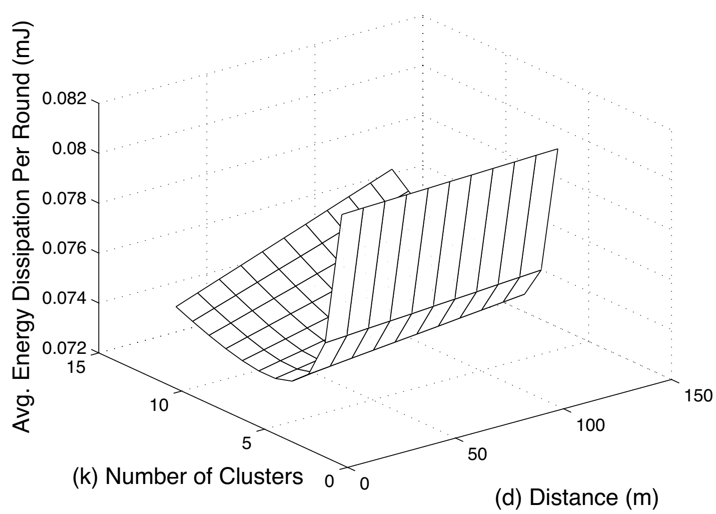

Figure 11. Average energy dissipation versus no. of clusters and distance for Zhu and Papavassiliou energy model. Distance with $N_s = 100$ nodes, $M = 100$, $E_{fs} = 7\,\mathrm{nJ/bit/m^2}$ and $E_{mp} = 0.0013\,\mathrm{pJ/bit/m^4}$.

of clusters, and therefore, we can find the number of clusters that minimizes energy dissipation.

5. SIMULATION RESULTS

Our results are based on analyses and are validated by Matlab simulations. The hardware parameter values, such as, current required for sensor wake up and sleeping time, used in our simulations, are those of Mica2 Motes [32]. As in [22], we also use radio parameters, such as, sensor wake up and sleeping time, of the radios data sheet (Chipcorn, CC1000 datasheet) [31]. All parameter values used in our energy model (for both simulation and the analysis) are listed in Table 3. We also indicate in the Table the sources/references where these values are originated. Since our results are based on real device parameters, they are expected to reflect a true energy dissipation behaviour of the system.

In our simulations, we consider a sensor network with $N_s = 100$ sensor nodes. Consider our deployment area as the square $\{(0,0),(0,100),(100,0),(100,100)\}$ as in [11]. The base station or sink node is located in the coordinate $(50,175)$ which is outside the deployment area and connected to an external power supply. Initially, CHs are randomly placed within an $50\,\text{m} \times 50\,\text{m}$ square placed in the middle of the $100\,\text{m} \times 100\,\text{m}$ deployment area. All other sensor nodes in each cluster are randomly uniformly distributed in a circle of 25 m radius of their respective CH. For our simulation we consider practical sensor network with fixed clusters and single-hop transmission. We generate 1000 random setups, each with the above simulation setting. Therefore each simulation data point is obtained by averaging over 1000 random setups. We assume that the total number of sensors in the entire network N_s is 100, and each node reports data once every 300 ms ($T_{tr} = 0.3\,\text{s}$). The channel bandwidth was set to 1 Mb/s as in [11], each single packet size is $b = 2\,\text{kb}$, as in [25], which maintains a low average data rate requirement per node ($< 12\,\text{bps}$). Moreover, we assume energy dissipation for actuation, E_{actu}, is 0.02 mJ as in [34] and energy for starting up the radio, E_{ini} is 1 µJ as in [35]. Note that we do not account for energy dissipation in re-transmitting because of the packets collided in the simulations. As in [22], for our simulation, we used Mica2 Motes hardware values [32] and time values are based on radio's data sheet [31]. We assume that, being consistent with a LEACH application, a CH and a sensor node have the same radio. Sleeping time, $T_S = 299\,\text{ms}$, and wakeup time, $T_A = 1\,\text{ms}$, of the sensor node are considered, as in [22]. Self-discharge of batteries is considered, as 3% per year as in [26]. We conducted Matlab simulations with different parameter settings as described later. We consider processing and communication energy of the CH is 20% more, and sensing and logging energy is 10% more than that of regular sensor nodes. Therefore, we assume selection of the weighting factor, h_i, as $\{h_1, h_2, h_3, h_4\} = \{1.2, 1.2, 1.1, 1.1\}$.

Table 3. Parameter values used in energy model.

Symbol	Description	Value
N_{cyc}	Number of clock cycles per task	0.97×10^6 [30]
C_{avg}	Avg. capacitance switch per cycle	22 pF [31]
V_{sup}	Supply voltage to sensor	2.7 V [31]
f	Sensor frequency	191.42 MHz [27]
n_p	Constant: depending on the processor	21.26 [30]
n	Path loss exponent	2 or 4 [30]
I_0	Leakage current	1.196 mA [30]
V_t	Thermal voltage	0.2 V [27]
b	Transmit packet size	2 kb [25]
E_{elec}	Energy dissipation: electronics	50 nJ/bit [30]
E_{amp}	Energy dissipation: power amplifier	100 pJ/bit/m^2 [30]
T_{tranON}	Time duration: sleep → idle	2450 µs [22]
$T_{tranOFF}$	Time duration: idle → sleep	250 µs [22]
I_A	Current: wakeup mode	8 mA [32]
I_S	Current: sleeping mode	1 µA [32]
T_A	Active time	1 ms [22]
T_S	Sleeping time	299 ms [22]
T_{tr}	Time between consecutive packets	300 ms
T_{sens}	Time duration: sensor node sensing	0.5 mS
I_{sens}	Current: sensing activity	25 mA
I_{write}	Current: flash writing 1 byte data	18.4 mA [33]
I_{read}	Current: flash reading 1 byte data	6.2 mA [33]
T_{write}	Time duration: flash writing	12.9 mS [33]
T_{read}	Time duration: flash reading	565 µS [33]
E_{actu}	Energy dissipation: actuation	0.02 mJ [34]

5.1. Energy Comparison

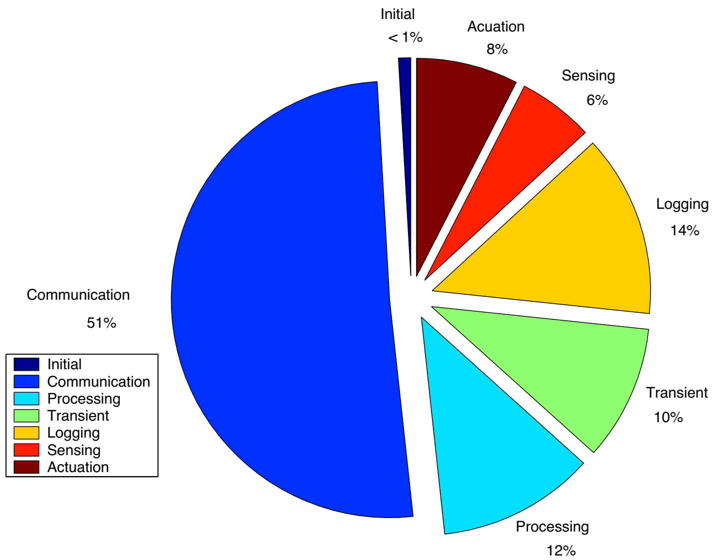

Figure 12. Energy consumption pie chart for any sensor in cluster j, when actuation is considered. Here we consider for $N_s = 100$ sensor nodes, $M = 100$, $k = 10$ clusters, $E_{fs} = 10\,\text{pJ/bit/m}^2$ and $E_{mp} = 0.0013\,\text{pJ/bit/m}^4$.

In Fig. 12 we present a pie chart describing the energy consumption for communication, processing, transient, sensor loggings and sensing, 51%, 12%, 10%, 14% and 6% of the total energy respectively. All of these sources of energy consumption are not negligible.

The same parameters, namely $N_s = 100$ sensor nodes, $M = 100$, $k = 10$ clusters, $E_{fs} = 10\,\text{pJ/bit/m}^2$ and $E_{mp} = 0.0013\,\text{pJ/bit/m}^4$, are used to generate Fig. 13 where we compare the effect of the difference energy models on the sensor network lifetime. Each simulation data point is obtained by averaging over 1000 random setups, but observe that the results does not change with single simulation.

We consider actuation performed only for this pie chart (Fig. 12) and exclude it from all other simulations, for the purpose of fair comparison with the other energy models that also exclude it. For all our simulation, we used an AA size alkaline battery with 1500 mAh. However, we also repeated our simulation for AA size alkaline battery with 700 mAh, C-cell battery with 5000 mAh and D-cell battery with

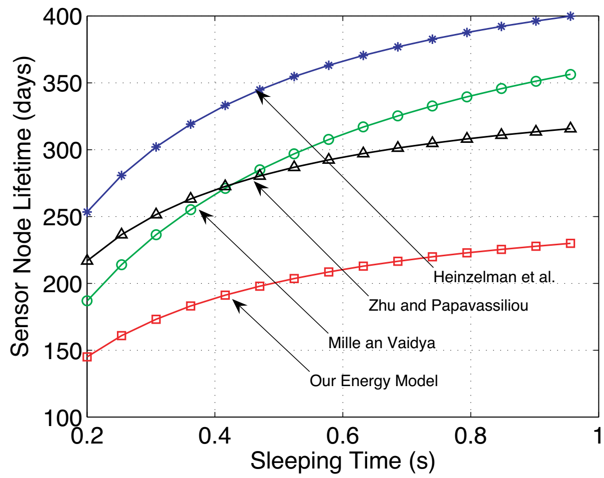

Figure 13. Sensor node lifetime verses sleeping time of the sensor node, with different energy models with AA alkaline batteries by using (5) and (6). Here we consider for $N_s = 100$ sensor nodes, $M = 100$, $k = 10$ clusters, $E_{fs} = 10\,\text{pJ/bit/m}^2$ [11] and $E_{mp} = 0.0013\,\text{pJ/bit/m}^4$ [11].

9000 mAh for 1.5 V and found that all results were consistent. Node lifetime can be computed by

$$\text{node lifetime} = \frac{\text{initial battery capacity}}{\text{avg. current} \times 365 \times 24} \quad \text{[years]},$$

where the units of the initial battery capacity is mAh and the avg. current is mA. In Fig. 13, we show that existing energy models overestimate life expectancy of a sensor node by 30–58%.

5.2. Effect of Free Space Fading Energy (E_{fs})

The optimal number of clusters derived in (15) is only applicable if free space fading energy is assumed to be constant [19] , which may not be the case in practice. For this reason, we repeated the above simulation by varying free space fading energy, E_{fs} within the interval $(1 - 10^4)$ [pJ/bit/m^2] and observed in Fig. 14 that when E_{fs} increases, the optimal number of clusters also increases.

We found that energy dissipation per round increases from 7.11% to 12.81% as the optimal number of clusters changes from 1 to 3. Moreover, we observe that when free space fading energy, $E_{fs} < 1670\,\text{pJ/bit/m}^2$ the optimal number of clusters needed is one and

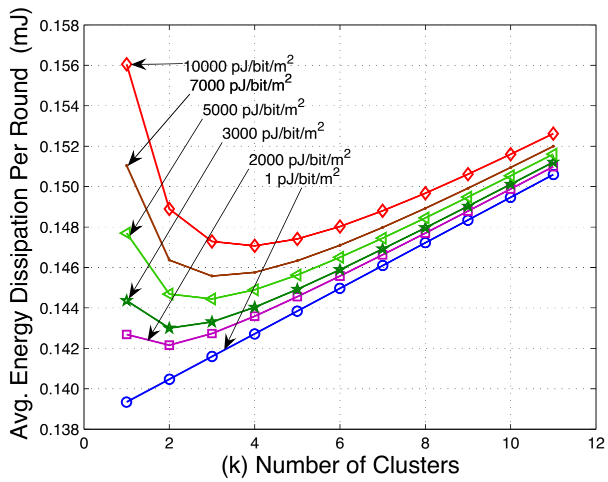

Figure 14. Average energy dissipation versus number of clusters when E_{fs} varies between $(1-10^4)\,\mathrm{pJ/bit/m^2}$ for our energy model. This shows when E_{fs} increase, optimal number of clusters also increases.

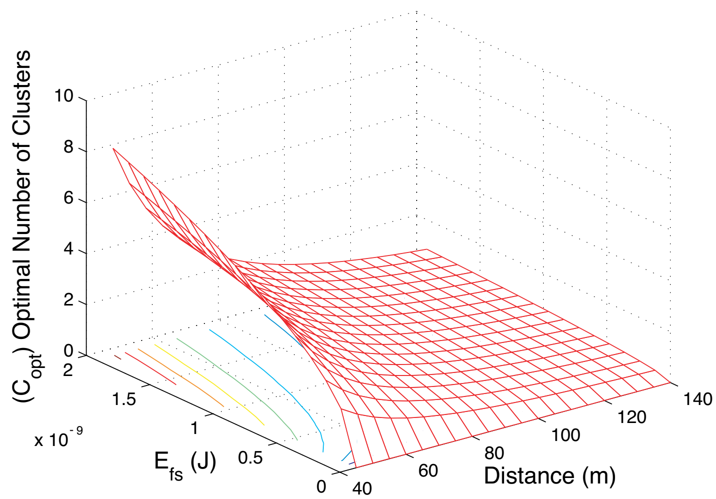

Figure 15. Relationship between E_{fs}, C_{opt}, and the distance for our energy model, when $E_{fs} = 10\,\mathrm{pJ/bit/m^2}$.

hence, clustering is not necessary. We repeated the simulation by increasing E_{fs} further, up to $10^5\,\mathrm{pJ/bit/m^2}$, and confirm that the

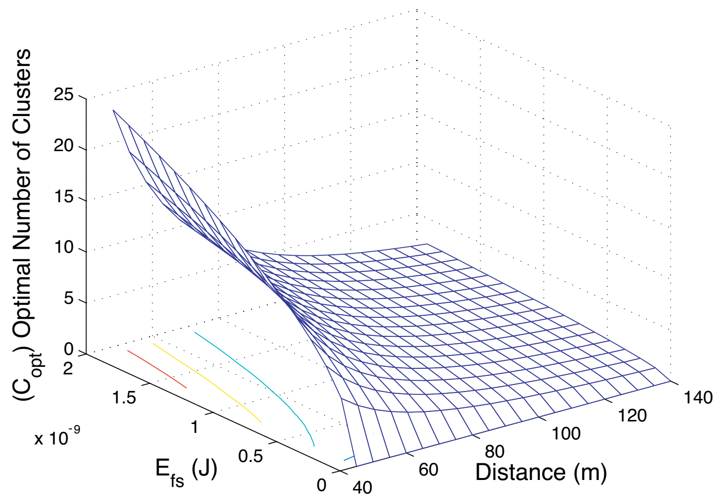

Figure 16. Relationship between E_{fs}, C_{opt}, and the distance for Heinzelman et al. energy model, when $E_{fs} = 10$ pJ/bit/m^2.

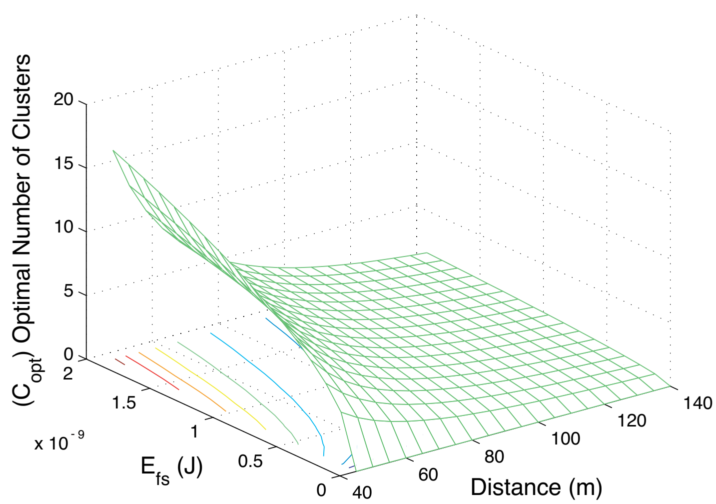

Figure 17. Relationship between E_{fs}, C_{opt}, and the distance for Mille and Vaidya energy model, when $E_{fs} = 10\,$pJ/bit/m^2.

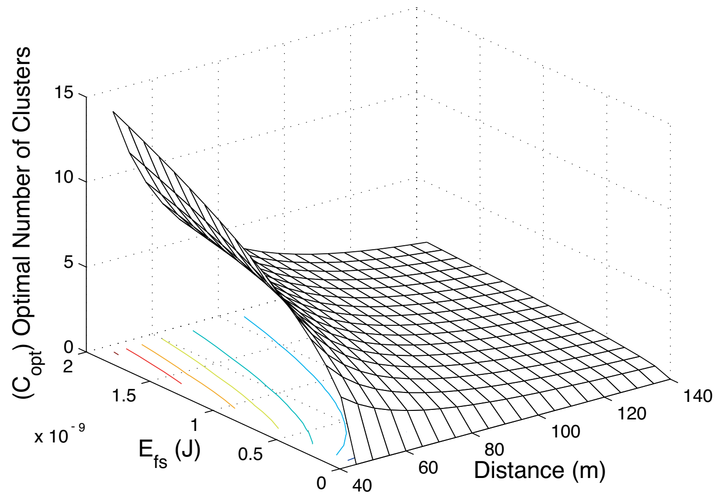

Figure 18. Relationship between E_{fs}, C_{opt}, and the distance for Zhu and Papavassiliou energy model, when $E_{fs} = 10\,\mathrm{pJ/bit/m^2}$.

optimal number of clusters becomes more important with higher free space fading energy dissipation. Observe that the average energy dissipation decreases with the increasing number of clusters, this is due to reducing communication distance.

According to Figs. 15–18, the number of optimal clusters increases with the increase of free space fading energy, E_{fs}, for all the above mentioned four energy models. Now we consider the same network but we vary the number of clusters k, free space fading energy, E_{fs}, and the distance from the CHs to the base station or sink node. Here we investigate the analytical results which derived in Section 3, 3.2 and 4 (see Fig. 15, 16, 17, 18, 19, 20). We observe that the optimal number of clusters decreases dramatically with the increasing distance. Energy differences between the models are shown in Fig. 19. For the particular case when the distance is equal to 100 m, the variation of the optimal number of clusters with free space fading energy is shown in Fig. 20.

5.3. Energy Difference E_D

Let E_D represent the percentage of energy difference between our energy model and the energy model in [11]. We found that the energy difference dramatically decreases when E_{fs} is contained within the interval $(1 - 5 \times 10^3)$ [pJ/bit/m^2]. We kept the optimal number of clusters as three and free space fading energy E_{fs} as 7×10^3 pJ/bit/m^2, and repeated the simulation. We observe that the sensor lifetime is increased by 12.74% when the sleeping time is 0.2 s, and by 13.92% when the sleeping time is 0.4 s, when the number of clusters used is reduced from 10 (non optimal clusters) to 3 (optimal clusters).

5.4. Effect of Physical Area of Sensor Network

Next, we vary the number of sensor nodes N_s and the physical area M to their effect on the distance, free space fading energy, and the number of optimal clusters. In addition, we consider how sensor network lifetime can be maximized and the number of sensors required to design a network for a given lifetime. As demonstrated in Fig. 21, the optimal number of clusters vary linearly with M (the square root of the physical area). Importantly, the effect of free space fading energy, E_{fs}, becomes less by increasing the distance as in Fig. 22.

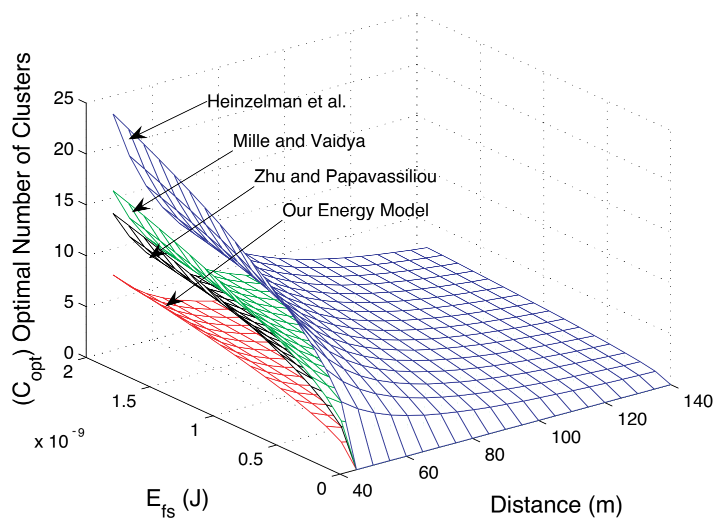

Figure 19. How optimal number of clusters, C_{opt}, vary for different energy models, when $E_{fs} = 10$ pJ/bit/m^2. Relationship between free space fading energy, E_{fs}, optimal number of clusters, C_{opt}, and the distance.

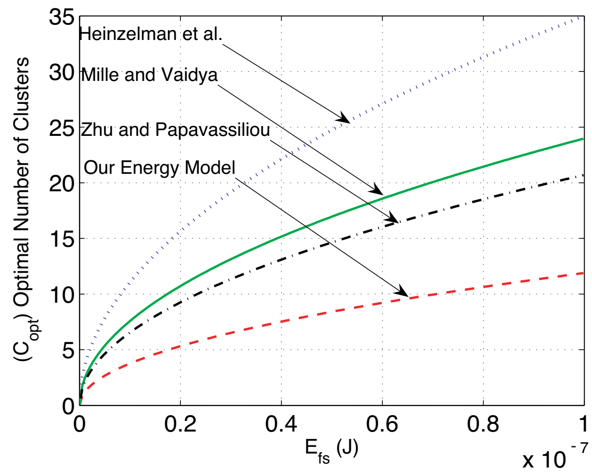

Figure 20. How optimal number of clusters, C_{opt}, vary for different energy models, when $E_{fs} = 10\,\text{pJ/bit/m}^2$. Relationship between optimal number of clusters, C_{opt}, and free space fading energy, E_{fs}.

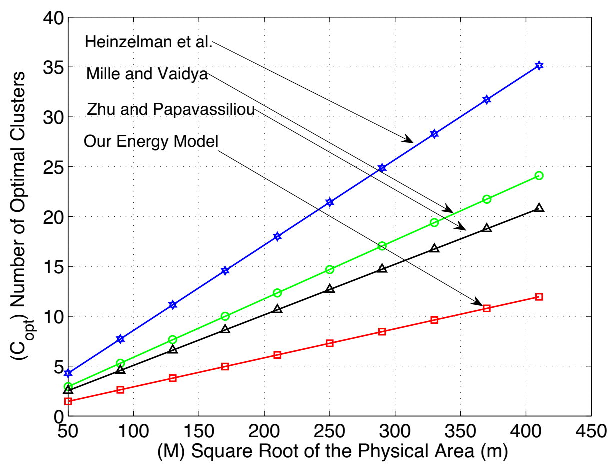

Figure 21. C_{opt} versus square root of the physical area in all energy models, when $E_{fs} = 10\,\text{pJ/bit/m}^2$.

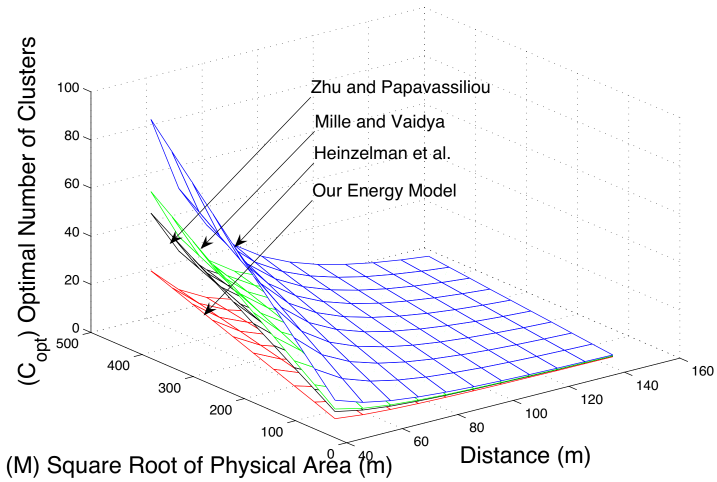

Figure 22. When distance form CH to base station vary, how C_{opt} vary with square root of the physical area in all models, when $E_{fs} = 10\,\text{pJ/bit/m}^2$.

5.5. Effect of the Duty Cycle

Finally, we vary the number of duty cycles to investigate the affect on energy consumption. (see Fig. 23). As shown in Fig. 23, when the number of duty cycles increases, interestingly, the average energy consumption of all models diverge. When the number of duty cycles is 1, the maximum over-estimation of our energy model relative to Heinzelman energy model is observed as 46.77%.

5.6. Percentage of Nodes Alive

The lifetime of a sensor network depends on the application where the sensors are deployed. Therefore, we investigate how the number of live sensor nodes varies with the number of rounds or time. An over-estimation is shown in Fig. 24 where the number of sensor nodes that live is plotted against the number of rounds. The maximum over-estimation of the death of the last node of our energy model relative to the Heinzelman energy model is 47.95%. We repeated the all above simulations for AAA, C-cell and D-cell batteries and found the results to be consistent.

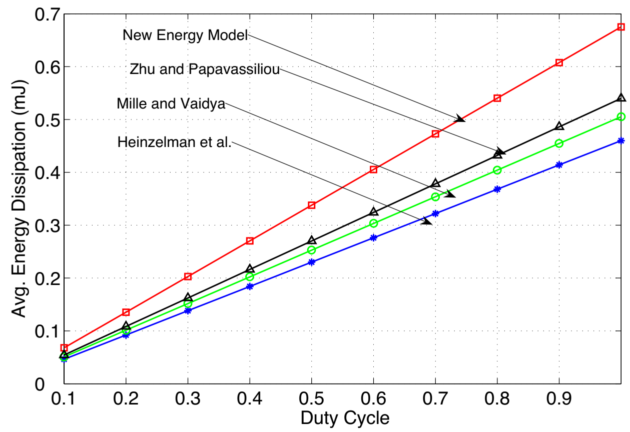

Figure 23. Average energy dissipation per sensor node versus duty cycle in energy models. Here we consider for $N_s = 100$ sensor nodes, $M = 100$, $k = 10$ clusters, $E_{fs} = 10\,\mathrm{pJ/bit/m^2}$ [11] and $E_{mp} = 0.0013\,\mathrm{pJ/bit/m^4}$ [11].

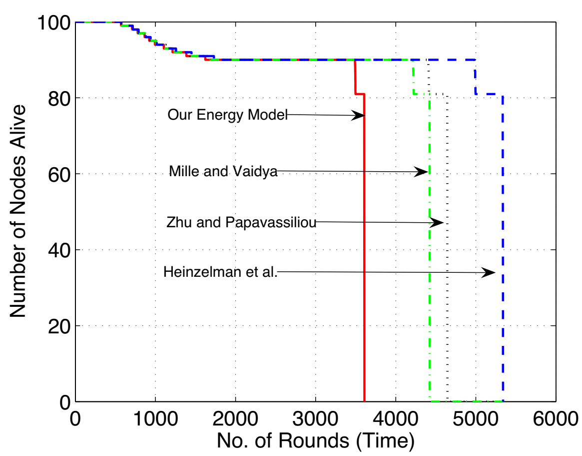

Figure 24. How the number of live nodes varies with the number of rounds (time), comparing all energy models.

5.7. Effects of Number of Sensors and Distance of CHs from Sink Node

We investigate how the number of sensors affects the optimal number of clusters and the sensor node lifetime, in a given physical area.

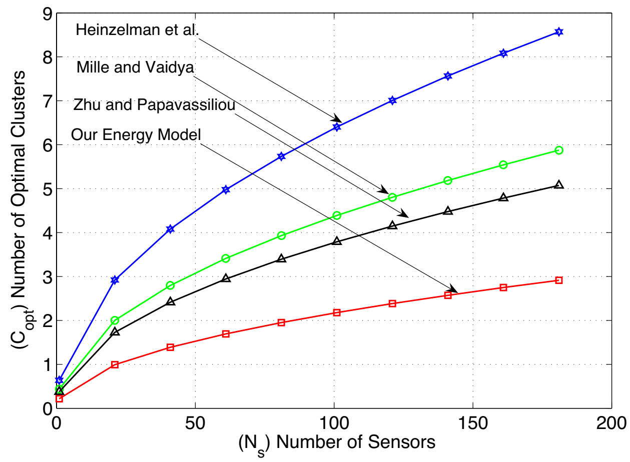

Figure 25. How the optimal number of clusters, C_{opt} versus number of sensors (analytical results) for a square root of the physical area $M = 100$ and $E_{fs} = 10\,\text{pJ/bit/m}^2$.

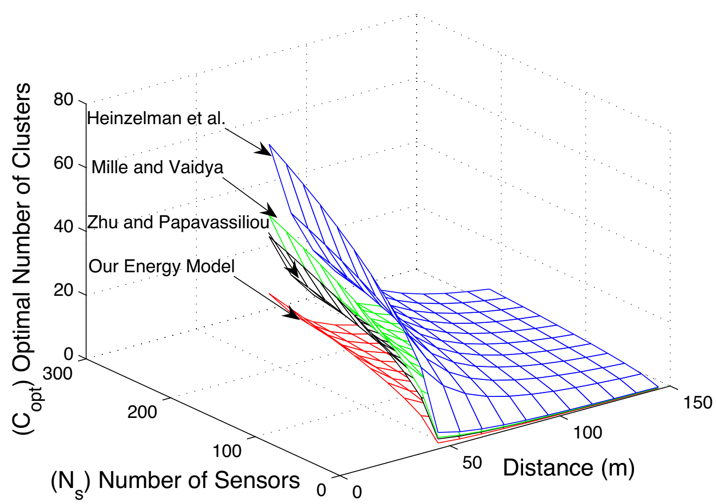

Figure 26. How the optimal number of clusters, C_{opt} versus the number of sensors and the distance from CH to base station for a square root of the physical area $M = 100$ and $E_{fs} = 10$ pJ/bit/m^2.

The optimal number of clusters increases with the number of sensors used for all energy models as shown in Fig. 25 and decreases with the distance as in Fig. 26. It is clear that this change is far less for the proposed energy model in comparison to the Heinzelman method. According to our energy model, a moderate increase in the number of sensors used may not result in the change of design parameters concerning the optimal number of clusters. By (2), $E \propto d^2$, one may expect that when the number of sensors is doubled the sensor lifetime is multiplied by four. However, as we show this is not the case. Let us consider sensor deployment with uniform distribution. According to

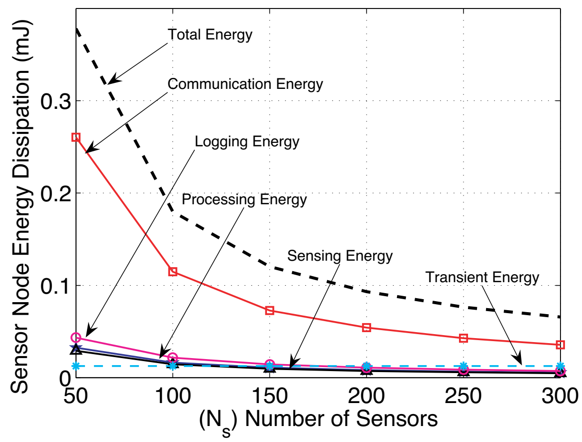

Figure 27. All energy components with sensor node lifetime versus number of sensors for $E_{fs} = 10\,\mathrm{pJ/bit/m^2}$ and a square root of the physical area $M = 100$, for uniform deployment, with increasing number of sensors.

Fig. 27, all energy dissipations converge when the number of sensors is increased. Therefore, the change in energy dissipation with respect to the change in the number of sensors becomes less. It should be noted that sensor node lifetime is inversely proportional to the total energy consumption of the sensor node:

$$sensor\ lifetime \propto \frac{1}{total\ energy\ consumption},$$

according to which, the plot of sensor node lifetime should approximately resemble the inverse of the plot of total energy consumption. As can be seen from Fig. 27, all energy consumption types, except transient energy, decrease with the increasing number of sensors.

Table 4. Sensor node lifetime when increasing number of sensors, with uniform sensor deployment, when $E_{fs} = 10\,\text{pJ/bit/m}^2$.

No: of Sensors (N_s)	C_{opt}	Radius = $\frac{M}{\sqrt{\pi C_{opt}}}$ [m] (Circular Cluster)	Length = $\frac{M}{\sqrt{C_{opt}}}$ [m] (Square Cluster)	Length = $\sqrt[4]{\frac{4}{27}}\frac{M}{\sqrt{C_{opt}}}$ [m] (Hexagonal Cluster)	Avg. Distance [m] Simulation Node→CH
50	1	56.4190	100	62.0403	36.9804
100	2	39.8942	70.7107	43.8691	25.5901
150	3	32.5735	57.7350	35.8190	20.1241
200	3	32.5735	57.7350	35.8190	19.1248
250	4	28.2095	50	31.0202	17.5014
300	4	28.2095	50	31.0202	17.5125

In Table 4, the same number of optimal clusters ($C_{opt} = 4$) is assigned when the number of sensors are 150 and 200 making cluster radius stay the same. Interestingly, the simulation also shows that the average number of cluster radius increases from 17.5014 to 17.5125 m, also increasing the sensor lifetime. This is mainly due to the decrease in the number of bits to be transmitted. Note that when the number of sensors increases, the average number of bits sent by each sensor decreases so that the total amount of information in a network is kept constant at 10^5 bits. Knowing C_{opt} and M for a given network, we evaluate and present the average radius of a circular cluster in the 3rd column of Table 4, the average length of a square cluster in the 4th column, and the average circum radius of a hexagon in the 5th column. Network designers can then use these values to optimize network lifetime.

We investigate how the optimal number of clusters, C_{opt}, varies as a function of the number of sensors and area, when one million sensors are deployed, as shown in Table 5. We observe that the optimal number of clusters increases with the increased number of sensors and area. For example, it is observed that 58 clusters are needed for a million sensors and no clustering for 100 sensors, and $M = 100$ m, when the distance from the CH to the sink node or base station is 145 m when $E_{fs} = 10\,\text{pJ/bit/m}^2$ is maintained. We also observe that network lifetime can be increased up to 7.3337 years for a million sensors by assuming that the minimum required number of bits to be transmitted is 200 per round. We cannot decrease the number of bits of the data to be transmitted, as the number of sensors grow, or sensors will fail to transmit the information. Depending on the application we may increase the sensor sleep time instead of reducing the number of bits.

Table 5. Optimal clusters (C_{opt}) with square root of physical area (M) and number of sensors (N_s), when $E_{fs} = 10\,\mathrm{pJ/bit/m^2}$.

M	(N_s) Number of Sensors					
[m]	100	400	800	10×10^3	10×10^4	10×10^5
100	1	2	2	6	19	58
200	1	3	4	12	37	116
300	1	4	5	18	55	174
400	2	5	7	24	74	232
500	2	6	9	29	92	290

6. DISCUSSION

LEACH is a hierachical routing protocol which used cluster based approach in wireless sensor network. It is an example that directly extends the cellular TDMA model to sensor networks [36]. It uses rotation CH method in each communication round. Therefore, LEACH forms new clusters and CHs in each round. These include energy dissipation due new cluster formation including rotating CH, E_{form}. This is only relevant to rotating CH based protocols, such as LEACH. By rotating cluster heads, LEACH distributes the energy load among all the nodes, so that the network's lifetime is increased. Unfortunately rotating cluster heads in every communication round dissipates battery energy unnecessarily.

To define a network scenario in which a particular choice of sensor nodes are CHs — one in each cluster. Let S be the set of network scenarios. As there are n_j+1 sensors in a cluster j, the total number of network scenarios (the cardinality of S) is given by $|S| = \prod_{j=1}^{k}(n_j+1)$. Let $d_j(s)$ be the distance from the CH_j to the next CH (or sink) in a network scenario s ($s \in S$). For each $s \in S$ and each cluster j, let $E_{CH}(s_j)$ be the energy consumed by CH_j and $E_N(s_{ij})$ be the energy consumed by sensor i in cluster j, both in scenario s. Replacing d_j with $d_j(s)$ in (5) and (6) enables us to obtain $E_N(ij)$ and $E_{CH}(j)$ values respectively. Let T_s be the proportion of time the system spends in network scenario s, $s \in S$. The average energy consumption of any sensor in cluster j in such a LEACH-type protocol per round is estimated by

$$E_L(j) = \frac{1}{(n_j+1)} \sum_{s=1}^{|S|} T_s \left[E_{CH}(s_j) + \sum_{i=1}^{n_j} E_N(s_{ij}) + E_{form} \right], \qquad (17)$$

and the total energy consumed by the entire network per round is given by

$$E_{tot_L} = \sum_{j=1}^{k} E_L(j).$$

This gives rise to many interesting questions of how to optimize the T_s values and the sleep and active times to maximize network lifetime.

7. CONCLUSION

In this paper, we have proposed a new, realistic and comprehensive energy model for wireless sensor networks. The energy consumption between different sources in the considered set up of a sensor node were analyzed. The results indicate that, simple energy models over-estimate the real sensor node lifetime. We also have applied our model to a LEACH-type protocol to obtain an accurate evaluation of the energy consumption and node lifetime. The paper inspires new interesting and useful avenues to maximize sensor network lifetime. Energy consumption by Heinzelman et al. [11] is over-estimated life of a sensor node by 51–58%, Zhu and Papavassiliou [15] by 32–41%, and Mille and Vaidya [22] by 30–35%.

We have concluded that the number of clusters does not play significant role for moderate size sensor networks if the free space fading energy is low. For large networks, on the other hand, cluster optimization is still important even if free space fading energy is low. Moreover, we have shown that the optimal number of clusters is very sensitive to the energy model used. We observe that over-estimation of the last node death is 30.1% when the number of the sensor nodes is plotted against the number of rounds (time). This paper also provides an estimation of the number of sensor nodes needed to design a network for a given lifetime, with all the important factors that influence to the life expectancy of sensor networks.

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