Increasing Lifetime of a Two-Dimensional Wireless Sensor Network Using Radio Range Adjustments

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SUMMARY  Optimizing lifetime of a wireless sensor network has received considerable attention in recent years. In this paper, using the feasibility and simplicity of grid-based clustering and routing schemes, we investigate optimizing lifetime of a two-dimensional wireless sensor network. Thus how to determine the optimal grid sizes in order to prolong network lifetime becomes an important problem. At first, we propose a model for lifetime of a grid in equal-grid model. We also consider that nodes can transfer packets to a grid which is two or more grids away in order to investigate the trade-off between traffic and transmission energy consumption. After developing the model for an adjustable-grid scenario, in order to optimize lifetime of the network, we derive the optimal values for dimensions of the grids. The results show that if radio ranges are adjusted appropriately, the network lifetime in adjustable-grid model is prolonged compared with the best case where an equal-grid model is used.

key words: wireless sensor networks (WSNs), radio range adjustment, network lifetime, energy consumption, grid lifetime

1. Introduction

Wireless sensor nodes have emerged as a result of recent advances in Micro-Electro-Mechanical Systems (MEMS) technology which results in low power transceiver design and wireless sensor technology. These nodes can form a network in an ad hoc fashion and are electrically powered by only one or two small batteries. It is infeasible to replace batteries of nodes due to the large number of nodes and possibly harsh terrain and hostile environment in which they are deployed. Therefore, the most important problem in these networks is to perform its operations in an efficient manner to prolong their lifetimes. According to different application scenarios, the network lifetime can be defined as the time duration before 1) the first node dies, 2) the power of a certain percentage of active nodes drops below a threshold or 3) a loss of coverage occurs in the network due to mobility or failure of some nodes [8]. In this paper, we assume network lifetime is time span from the instant when the network is deployed to the instant when the first grid dies i.e. the power of all sensor nodes in the grid drops below a threshold.

There are two major communication techniques for transmitting data from a source to a sink: single-hop communication and multi-hop communication [4]. In multi-hop communications, nodes next to sink nodes have to relay much more traffic than far from sink ones because in addition to their own traffic, they have to relay other nodes’ traffic. Therefore, the energy dissipation speed of these nodes is greater than that of the other nodes, and their batteries deplete more rapidly. However, in single-hop communications, nodes far from sink experience high energy drainage because of higher distances. Hence, this highly non-uniform energy usage causes some sensors to die earlier than others resulting in severe degradation of network coverage and connectivity and drastic reduction of overall network lifetime.

To address the above problem, much research effort has been directed to attain efficient and uniform energy usage among sensors. Some of these techniques include deployment strategy [8], [11] and [10]. In [11], Maleki and Pedram proposed a sensor deployment strategy considering sensors having increasing initial energy towards the sink to avoid early collapse due to heavy incoming traffic in multi-hop transmission. A similar lifetime extending deployment strategy based on non-uniform sensor density instead of initial energy was proposed in [10]. But above methods, for their difficult implementations, are not applicable in actual WSNs.

Recently, radio range adjustment, another effective approach, has prompted many researchers to reduce transmission power by adjusting nodal radio transmission ranges, thus network life is prolonged while preserving network properties e.g., coverage or connectivity. The benefits of adjusting transmission range of sensor nodes for purpose of saving energy have been further demonstrated in [6], [9], [13] and [2].

Topology management algorithms are other methods to increase network lifetime. They let redundant nodes go to sleep state; hence network lifetime is prolonged while connection and capacity of the networks are preserved. GAF [16] is a topology management protocol which is based on division of sensor network in a number of virtual grids to improve energy efficiency. Grid sizes are chosen such that all nodes in a grid are equivalent from a routing perspective. This means that any node in each grid can communicate with any node in other adjacent grids. According to GAF model, there should always be in each grid one or more active nodes forming network backbone. GAF only keeps one node awake in each grid, while the other nodes, which do not have transmission or relay tasks, put their radios in sleep mode to save more energy. To balance out the energy consumption, all nodes of a grid will be selected as active nodes in a rotational manner based on their residual energy.
According to GAF algorithm, if we increase radio transmission range of nodes, each grid includes more nodes hence more redundant nodes can make transition into sleep state and therefore a longer network lifetime can be achieved. On the other hand, energy consumption in transmission state increases super-linearly with radio transmission range. Thus in grid-based clustering schemes, determining optimal grid sizes in order to prolong network lifetime is an important problem.

Based on the frame work in [16], some works only considered a linear network (where the nodes exist along a line) e.g. [3], [5], [7], [12], [14], [15], [17] and [18] which is a less realistic scenario. The authors in [5] analyzed energy consumption in both equal- and adjustable-grid models. However, they have not considered the network lifetime which is not entirely determined by energy saving. Therefore, it cannot increase lifetime of sensor network significantly, because the model has uneven power consumption. This means that some of sensor nodes will die faster than others. The sensor nodes, neighboring to sink nodes, consume much more energy than those far from the sink, because these nodes must relay other nodes’ data in addition to their own data. These nodes determine lifetime of the network.

In [4], the authors increase network lifetime through reducing energy consumption of the network. They also derive optimal grid lengths in equal- and adjustable-grid models, but for more increasing lifetime, they use nodes re-deployment method which is not easy to implement in actual WSNs.

In this paper we consider a two-dimensional wireless sensor network and determine optimal transmission range in equal-grid model and adjustable-grid model. We investigate trade-off between traffic and transmission energy consumption considering that nodes can transfer packets to a grid which is two or more grids away. We derive dimensions of grids in order to increase lifetimes of all grids regardless of their distances from the sink.

The remainder of this paper is organized as follows. In Sect. 2, we describe energy consumption model. We introduce our two-dimensional network model and determine optimal grid length in equal-grid model in Sect. 3. In Sect. 4, we determine optimal dimensions of grids in adjustable-grid model. In Sect. 5, we draw a conclusion to this paper.

2. Energy Consumption Model

In WSNs, data communication between nodes strongly dominates other node functions such as sensing and processing. We consider three components of energy consumption for each node in the network:

a) Transmission Energy: Airborne radio transmissions are attenuated by a path loss at a rate that scales in a power-law with distance [5]. The energy, consumed per second, in transmission state is,

\[ E_t = (e_t + e_{tr}^n)BA_t \]  

where \( e_t \) and \( e_{tr}^n \) are dependent on the energy dissipated by transmitter electronics and amplifiers. Both \( e_t \) and \( e_{tr}^n \) are properties of the transceiver used by nodes; \( r_t \) is the range of the transmitter, and \( n \) is path loss exponent, a factor that depends on RF environment. Typical values for \( n \) are between 2 and 4, which the value of 2 is the path loss exponent for free space. B is data bit rate and is fixed in our study. \( A_t \) is traffic transmitted by the node in Erlangs.

b) Receive Energy: Energy consumed for reception is not dependent on the distance between transmitter and receiver. This energy is calculated according to following equation,

\[ E_r = e_r BA_r \]  

where \( e_r \) is dependent on energy dissipated by receiver electronics. B is data bit rate. \( A_r \) is traffic received by the node in Erlangs.

c) Energy consumption in idle listening: Actual radios consume power not only when sending and receiving data, but also when listening. This energy is dependent on traffic received by node. If the received traffic is \( A_r \) Erlangs, then idle energy consumption is,

\[ E_i = k e_r B(1 - 2A_r) \]  

where \( k \) is ratio of idle energy to receive energy. According to specification in [1], which is typical RF transceiver in sensor networks, the ratio between energy consumption in idle and reception modes is 1/40, therefore in this paper we assume that \( k = 1/40 \). Typical values of above parameters are shown in Table 1.

Since path loss increases exponentially by distance, total transmission energy can be reduced significantly using a multi-hop approach i.e. dividing a long transmission path into several shorter ones. If number of divisions is very large, the term \( e_{tr}^n \) is less than \( e_t \) in Eq. (1) and receive energy. If N is number of divisions, there is at least one specific N in which network lifetime maximizes. Now the problem is how the optimal range for energy efficient routing can be achieved.

3. Equal-Grid Model

Let us consider multi-hop communication in a two-dimensional network in which nodes distributed uniformly in a rectangular area. The sink is located in the middle of a side of the network. The density of nodes is \( n_s \) per square meter.

As shown in Fig. 1, the network is divided into \( 2N_y \)

| parameter | value |
|-----------|-------|
| \( e_t \) | \( 50 \times 10^{-9} \) J/bit |
| \( e_r \) | \( 50 \times 10^{-9} \) J/bit |
| \( e_d \) | \( 100 \times 10^{-12} \) J/bit/m², (for \( n = 2 \)) |
| B         | 1 Kbit/s |

Table 1: Typical values of energy consumption parameters for sensor nodes.
Transmission range of nodes of the $i$th grid in the $j$th strap should be long enough so that a node can communicate directly with any fore, the transmission range of sensor nodes should be long enough so that a node can communicate directly with any grid should be the same from a routing perspective. There-

equal straps. If network has dimensions of $D_x$ and $D_y$ meters for its length and width respectively. Each strap has length of $D_x$ meters and width of $W = \frac{D_y}{N_y}$ meters. A strap is also divided into $N_x$ equal grids. The widths of grids are the same as widths of straps, but their lengths are equal to $R = \frac{D_x}{N_x}$ meters. Based on GAF mechanism, all nodes in each grid should be the same from a routing perspective. Therefore, the transmission range of sensor nodes should be long enough so that a node can communicate directly with any nodes in a grid which is $M$ grids away in the same strap. Transmission range of nodes of the $i$th grid in the $j$th strap ($r_{ij}$) can be obtained from following equation:

$$r_{ij} = \begin{cases} \sqrt{(iR)^2 + (jW)^2} & , \ i \leq M \\ \sqrt{(iM + 1R)^2 + W^2} & , \ i > M \end{cases}$$  (4)

As shown in Fig. 2. In addition to its own generated traffic, each grid $i$ should send total traffic generated in some farther grids to grid $i-M$.

For computing traffic received by a grid, we assume each node produces $\alpha$ Erlangs of sensor data. Therefore, total traffic received and transmitted by the $i$th grid in the $j$th strap is $A_{n,i} = \left\lfloor \frac{N_{x,i}}{M} \right\rfloor RW\alpha n_i$ and $A_{t,i} = (\left\lfloor \frac{N_{x,i}}{M} \right\rfloor + 1)RW\alpha n_i$, respectively. According to Eq. (1), we can compute energy consumed in transmission state for the grid as $E_{t,i} = (e + e_{dr}r_{ij}^2)BA_{t,i}$, Where $r_{ij}$ can be obtained from (4). The energies consumed for reception and idle listening are calculated from (2) and (3) respectively; $E_{r,i} = eBA_{r,i}$ and $E_{i} = keB(1 - 2A_{r,i})$.

Total energy consumption of the grid ($E_{ij}$) is summation of energies consumed for transmission ($E_{t,i}$), reception ($E_{r,i}$) and idle listening ($E_{i}$) of the grid; i.e., $E_{ij} = E_{t,i} + E_{r,i} + E_{i}$.

In order to balance energy consumption between different nodes of a grid, active nodes are selected in a rotational manner according to their residual energies. This results in finishing the energies of grid nodes at the same time. Therefore, lifetime of the $i$th grid in the $j$th strap ($L_{i,j}$) is the ratio of total battery energies of the grid nodes to energy consumed by the grid. We assume there is the same amount of energy exists in batteries of nodes. If $n_{ij}$ denotes the number of nodes in the grid and $E_b$ denotes the amount of energy initially exists in each node, we can determine lifetime of the grid ($L_{i,j}$) as follows: $L_{i,j} = \frac{n_{ij}E_b}{E_{ij}}$, where $n_{ij} = n_iRW$.

Network lifetime ($L$) is the minimum of all grid lifetimes; i.e. $L = \min \{L_{i,j} | 1 \leq i \leq N_x, 1 \leq j \leq N_y \}$. In Fig. 3, network lifetime is plotted versus different values of $N_x$ and $N_y$. The network lifetime has the highest value of $L_{\max} = 1.011 \times 10^7$ s for $N_x = 3$ and $N_y = 7$. In our analysis, we use following values for other parameters: $M=1$, $D_x = 600$ meters, $D_y = 500$ meters, $E_b = 1$ joule, $n_i = \frac{1}{10}$ per square meter and each node produces data of $\alpha = 3 \times 10^{-6}$ Erlangs.

According to optimum value of $N_y = 7$, the network is divided into 14 equal straps. We consider one of two nearest straps to BS ($j=1$). In Fig. 4, lifetime of the strap is plotted versus different numbers of equal divisions according to different values of $M$ from 1 to 4. With increasing $M$, the traffic received by each grid reduces, but according to (4), increasing $M$ results in increasing $r_{ij}$ and this also results in increasing transmission energy. As can be seen in Fig. 4, the network lifetime has the highest value of $L_{\max} = 2.533 \times 10^7$
Fig. 4  Lifetime of the first strap (j=1) versus different numbers of equal divisions for different values of M.

Fig. 5  Lifetimes of grids of the first strap in equal-grid model (M=2, N_x = 20).

s, which occurs when M=2 and N_x = 20, which is improved by 11.3% compared to the best case when M=1 (L_{max} = 2.248 \times 10^7 \text{ s}). The grid lifetimes of the first strap, for the case when M=2 and N_x = 20, are shown in Fig. 5.

As shown in Fig. 5, lifetimes of the third and fourth grids are minimum because these grids relay much data than other grids except the first and second ones. These grids determine lifetime of the network because nodes of these grids will die earlier than others. Finishing energies of these grids results in disconnecting the network. Lifetimes of the first and second grids are not minimum because their transmission ranges are respectively $\sqrt{R^2 + W^2}$ and $\sqrt{(2R)^2 + W^2}$. Instead of $\sqrt{(3R)^2 + W^2}$ for other grids.

For previous figures, we assume that path loss exponent equals 2 (n=2) which represents free-space radio propagation. However, n tends to be larger in some sensor networks, whose typical value is 3.5. In Fig. 6, optimal number of divisions (N_x) is plotted versus different path loss exponents whose values are between 2 and 3.5. As can be seen in Fig. 6, N_x will increase when n increases. This means that by increasing n, transmission range should be decreased to reduce transmission energy.

4. Adjustable-Grid Model

According to previous section, nodes near the sink relay more traffic than nodes far from the sink. On the other hand, transmission ranges related to different grids are not the same. Due to this non-uniformity, we don’t reach to longer network lifetimes using equal-grid model. It seems that an adjustable-grid two-dimensional GAF model is needed and if properly designed can lead to a longer network lifetime. As shown in Fig. 7, in adjustable-grid two-dimensional GAF model, network is divided into 2n variable-width straps in which the jth strap divided into m_j variable-length grids.

In order to determine lengths and widths of grids of the jth strap, we start with the first grid of the strap. In order to determine W_j and R_{ij} in which 1 \leq j \leq n, lifetime equation for adjustable-grid model should be considered. The energy consumed for transmission state of the grid is:
After evaluating grid lifetimes, in order to determine optimal lengths of the grids, we have to solve following equation: \( L_{ij} = \frac{n_{ij} E_{ij}}{\sum_{i=1}^{M} W_j n_i \alpha} \) where \( E_{ij} = \frac{D - \sum_{i=1}^{M} R_i}{M} W_j n_i \alpha \), and \( A_{ij} = \frac{D - \sum_{i=1}^{M} R_i}{M} W_j n_i \alpha \).

The previous equation has one real positive root because \( f(W_j) \) has a minimum with negative value in zero \( f(0) = -\frac{M k_e}{\omega_{\text{desired}}} \) and for values \( W_j > 0 \), function \( f \) is strictly increasing. In Fig. 8, for \( M=2 \), optimal values of strap widths are plotted.

Lifetime of the \( i \)th grid in the \( j \)th strap can be calculated according to following relation: \( L_{ij} = \frac{n_{ij} E_{ij}}{\sum_{i=1}^{M} W_j n_i \alpha} \) in which some parameters are as follows:

- \( n_{ij} = \frac{R_j W_j n_i}{E_{ij}} \)
- \( E_{ij} = E_{ij} + E_{i,j} + E_{i,j} \)
- \( E_{ij} = (e_i^2 + \frac{\omega_{\text{desired}}}{2} + \omega_{\text{desired}} M k_e) B A_{ij} \)
- \( A_{ij} = \frac{D - \sum_{i=1}^{M} R_i}{M} W_j n_i \alpha \)
- \( E_{ij} = e_i A_{ij} B \)
- \( E_{ij} = k_e B (1 - 2 A_{ij}) \)
- \( A_{ij} = \frac{D - \sum_{i=1}^{M} R_i}{M} W_j n_i \alpha \)

Where \( r_{ij}^2 \) is:

\[
 r_{ij}^2 = \frac{\left( \sum_{i=1}^{M} R_i \right)^2 + \left( \sum_{i=1}^{M} W_j \right)^2}{\sum_{i=1}^{M} R_i^2 + W_j^2} \quad i \leq M
\]

\[
 r_{ij}^2 = \frac{\left( \sum_{i=1}^{M} R_i \right)^2 + \left( \sum_{i=1}^{M} W_j \right)^2}{\sum_{i=1}^{M} R_i^2 + W_j^2} \quad i > M
\]

After evaluating grid lifetimes, in order to determine optimal lengths of the grids, we have to solve following equation: \( \frac{\partial A_{ij}}{\partial c_{ij}} = 0 \). According to different values of \( i \) (number of grid in the strap), several possible answers are as follows:

1) \( i=1 \); in this case we have:

\[
 R_{ij}^2 = \frac{c_i}{c_{ij}} + \left( \sum_{i=1}^{M} W_j \right)^2 + \frac{c_i}{c_{ij}} (1 - 2k) + \frac{M k_e}{\omega_{\text{desired}}} \left( \sum_{i=1}^{M} R_i \right) W_j n_i \alpha
\]

2) \( i \neq M+1 \); in this case we have: \( R_{ij} = R_{M+1,j} \).

3) None of previous cases; in this case we have:

\[
 R_{ij}^2 = \frac{c_i}{c_{ij}} + \left( \sum_{i=1}^{M} R_i \right)^2 + W_j^2 + \frac{c_i}{c_{ij}} (1 - 2k) + \frac{M k_e}{\omega_{\text{desired}}} \left( \sum_{i=1}^{M} R_i \right) W_j n_i \alpha
\]

For straps far from the base station, we use a simple rule to determine grid lengths as follows: \( R_{ij} = \frac{D_n}{M \left[ \sum_{i=1}^{M} W_j \right]} \).

For increasing network lifetime, we should equalize lifetimes of the first \( M \) grids by changing their lengths in such a way that summation of lengths of the first \( M \) grids remains the same. According to above discussion the lengths and widths of grids are shown in Table 2. Network lifetime is \( 1.124 \times 10^7 \) s which is improved by 11.2% compared to the best case in equal-grid model.

5. Conclusions

Energy resource is one of critical constraints of WSNs to maximize their post-deployment active lifetime. Due to their simplicity and feasibility, we use grid-based clustering and routing schemes to increase lifetime of a two-dimensional network. After proposing a model for lifetime of a grid, we determine optimal value for grid dimensions.
in equal-grid model. We investigate trade-off between traffic and transmission energy consumption considering that nodes can transfer packets to a grid which is two or more grids away. We also evaluate network lifetime in adjustable-grid model and derive grid dimensions to increase network lifetime. Based on our results, adjustable-grid model has longer network lifetime compared with the best case when equal-grid model is used.

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