A Simple and Efficient Method to Mitigate the Hot Spot Problem in Wireless Sensor Networks

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Abstract. Much work on wireless sensor networks deals with or considers the hot spot problem, i.e., the problem that the sensor nodes closest to the base station are critical for the lifetime of the sensor network because these nodes need to relay more packet than nodes further away from the base station. Since it is often assumed that sensor nodes will become inexpensive, a simple solution to the hot spot problem is to place additional sensor nodes around the base stations. Using a simple mathematical model we discuss the possible performance gains of adding these supplementary nodes. Our results show that for certain networks only a limited number of additional nodes are required to fourfold network lifetime. We also show that the possible gain depends heavily on the fraction of nodes already present in the vicinity of the base station.

1 Introduction

The main task of most wireless sensor networks is to collect data and send it in a multi-hop fashion to a base station. While forwarding data in a multi-hop fashion to the base station is often more energy-efficient than transmitting the data directly from the sensing node to the base station, a potential disadvantage of the multi-hop strategy is that the nodes close to the base station must forward much more packets than nodes further away from the base station. Therefore, these nodes "typically die at an early stage" [7]. This is sometimes called the *hot spot* problem [1]. Without adding extra nodes or redistributing the available energy, this problem is hard to solve. For example, Perillo et al. have shown that varying the transmission power of nodes, even considering unlimited transmission ranges, does not solve the hot spot problem [7].

At the same time, it is also envisioned that sensor nodes will become "extremely inexpensive" [5]. While beyond a certain node density, adding additional nodes does not provide any improvement regarding sensing, communication or coverage [3], adding nodes might obviously help to increase the lifetime of a sensor network while providing the same service to its users, i.e. leveraging sensor values from the same number of nodes.

In this paper, we study the benefit of adding extra nodes to a sensor network using a mathematical model we developed previously [2]. Our results show that for certain networks only a limited number of additional nodes are required to fourfold network lifetime. We also show that the possible gain depends heavily on the fraction of nodes already present in the vicinity of the base station.

In the rest of this paper, we first provide an overview over our mathematical model. Section 3 presents the performance gains our model suggests. Before concluding, we discuss related work in Section 4.

2 A mathematical model for the lifetime of sensor networks

In this section we briefly present a mathematical model for the energy consumption of routings and lifetime boundaries of sensor networks presented earlier by Alonso et al. [2]. For the purpose of this paper, we concentrate on the lower bounds of the energy consumption of routings leading to an upper bound of the lifetime of a sensor network. For more details and the formal proofs, see [2].

The mathematical model considers continuous sensor networks [11]. In these networks, sensors sample data at regular intervals and transmit them to a base station, i.e. sensor nodes read sensor values, send them in a multi-hop fashion to a base station and go to sleep until the start of the next interval. Except for the leaf nodes that transmit only their own sensor readings, all nodes also forward readings of other nodes in each interval. This procedure continues until one or more nodes are depleted and connectivity is broken.

2.1 Energy consumption during one iteration

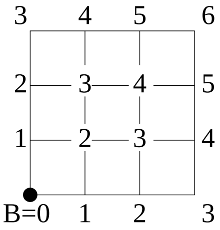

Fig. 1. A square grid sensor network partitioned in spheres

Our model partitions the set of all sensor nodes V into non-empty subsets S_0, ..., S_n satisfying $V = S_0 \cup S_1 \cup .. \cup S_n$, $S_i \cap S_j = \emptyset$ for all $i \neq j$. S_i is the set of nodes reachable from the base station B in i hops, but not less than i hops. Hence, $S_0 = \{B\}$. We call S_i the *sphere* of radius i around S_0. Figure 1 depicts an example network. Note that the current version of our model assumes that all nodes transmit at the same constant power. As some sensor network applications [4], our model implies that no data aggregation is performed, i.e. data is transmitted unchanged to the base station. Each node in sphere S_n, the sphere consisting of only leaf nodes, transmits exactly one packet in each iteration. A node in sphere S_{n-1} transmits the packets it receives from leaf nodes in sphere S_n plus one packet with its own sensor value.

Corresponding to the notion of spheres S, we introduce *balls* of radius i denoted B_i, with $B_i = S_0 \cup .. \cup S_i$. Further, we set $s_i = |S_i|$, $b_i = |B_i|$, $N = |V|$, and define

r as the energy consumption for receiving one packet and t as the energy required to transmit one packet. Using these definitions, we set

$$m_i = \frac{N - b_i}{s_i} r + \frac{N - b_i + s_i}{s_i} t. \tag{1}$$

In Equation 1, $N - b_i$ denotes the total number of nodes outside B_i, i.e. the total number of packets that the set of nodes in sphere S_i receives in each iteration. Hence, the nodes in S_i must forward $N - b_i + s_i$ packets in each iteration, namely the packets received from outer spheres plus their own s_i sensor readings. The best a routing algorithm can do is to equally distribute the energy consumption for receiving and transmitting packets across all the nodes in S_i, therefore the denominator s_i. Thus, m_i provides a lower bound on the energy consumption (for receiving and transmitting packets) for the node in S_i that consumes the most energy of all nodes in this sphere during one iteration.

For many sensor networks, $\max\{m_1, ..., m_n\}$ will be equal to m_1, i.e. the node that consumes most energy during one iteration is one hop away from the base station. An example of such a network is the one shown in Figure 1. In this case, we call S_1 the bottleneck sphere. Note that it is not always the case that sphere S_1 is the bottleneck sphere [2, 9].

2.2 Bounding network lifetime

For the majority of networks, the energy consumption m^T of the nodes in the bottleneck sphere for T iterations is $T \max\{m_1, ..., m_n\} = T m_i$; for a counterexample, see [2]. In these networks, the traffic can be distributed equally among the nodes in the bottleneck sphere. Hence, all nodes in the bottleneck sphere run out of energy during the same iteration, breaking connectivity. Example of such networks are the ones in Figure 1 and Figure 2. Note that the underlying assumption is that an optimal routing strategy is deployed since as discussed above m_i is a lower bound.

Suppose that each node initially has the same amount of energy denoted EE. Then, from the discussions above, it is obvious that the maximum number of iterations T_{max} a sensor network can perform before running out of energy under the given assumptions is bounded by the expression

$$T_{max} \leq \frac{EE}{\max\{m_1, ..., m_n\}}. \tag{2}$$

This means, that whatever routing we use, the sensor network cannot perform more than T_{max} iterations before connectivity breaks.

3 Performance Gains

Using the mathematical model described in the previous section, we now study the performance gains that are possible with additional nodes. Equation 1 enables us to identify the bottleneck sphere S_i and calculate the maximum energy consumption for the node in S_i that consumes the most energy of all nodes during one iteration, namely $max\{m_1, \ldots, m_n\}$.

Adding k_i additional nodes to sphere S_i, we can rewrite Equation 1 as

$$\overline{m}_i = \frac{N - b_i}{s_i + k_i} r + \frac{N - b_i + s_i}{s_i + k_i} t, \tag{3}$$

where as before r denotes the energy consumption for receiving one packet and t the energy required to transmit one packet. Equation 3 assumes an optimal scheduling that schedules the wake-up times (or radio-on times) accordingly. E.g. if we have a sphere with originally two nodes and add two additional nodes, we assume that the two original nodes can now sleep half of the time. During this time, the additional nodes are awake and take over the tasks of the original nodes, i.e. forwarding packets as well as taking sensor readings and transmitting the corresponding packets. This also implies that additional nodes can be located in the sphere so that they actually can take over the required task, i.e. they can receive packets from and send packets to the corresponding nodes. Further, $\overline{m}_i$ does not consider additional overhead such as the required time synchronization. Hence, as m_i, $\overline{m}_i$ is a lower bound. Note that this implies that the network provides the same service, i.e. the same amount of sensor readings are collected and transported to the base station during each iteration.

When adding additional nodes, Equation 3 enables to iteratively compute the current bottleneck sphere and add the next node into that sphere.

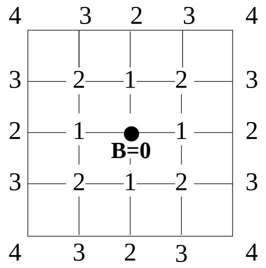

Fig. 2. A square grid sensor network with base station in the center of the grid.

For the lifetime calculations, we suppose each node initially has the exact same amount of energy EE. The maximum number of iterations T_{max} a sensor network can perform before running out of energy under the given assumptions is then bounded by Equation (2). For the actual calculations, we use the same values as previously measured on real hardware [9], namely a current consumption of 7.2 mA for transmitting and receiving with 20 ms transmission time and 30 ms reception time.

3.1 Regular Networks

We use grid networks with the base station in the corner (see Figure 1) and in the middle (see Figure 2). Figures 3 and 4 show the improvement of lifetime for differently sized

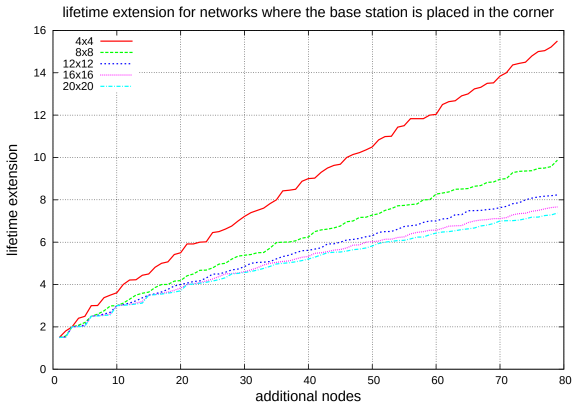

Fig. 3. Lifetime improvement for sensor networks where the base station is placed in the corner of the grid.

networks. For example, in Figure 3 we can see that with only 20 additional nodes (10% of the number of nodes for the largest network) the lifetime of sensor networks can be extended by approximately a factor four for medium-size to large networks.

While adding k nodes to a sphere S_i reduces the energy consumption for the nodes in that sphere, to minimize $\overline{m}_i$ and thus increase network lifetime, we potentially need to distribute the additional nodes over different spheres. Table 1 shows how to distribute the additional nodes over the different spheres, to obtain the maximum improvement of lifetime for each configuration, here for a 4×4 grid network with the base station in the corner as depicted in Figure 1.

Extra nodes	k_1	k_2	k_3	k_4	k_5	s_6	lifetime extension
2	2	0	0	0	0	0	1.8
4	3	1	0	0	0	0	2.4
8	5	3	0	0	0	0	3.4
16	8	5	2	1	0	0	4.8
32	13	10	5	3	1	0	7.5
48	19	14	9	4	2	0	10.2

Table 1. Example of how the additional nodes need to be distributed over the different spheres for a sensor network of size 4x4 in order to achieve the longest possible lifetime extension.

3.2 Random Networks

We also simulated networks where the nodes were randomly distributed among a certain area, that was either a rectangle with a size of 16×10 or circular with a radius of 10. We used different transmission ranges.

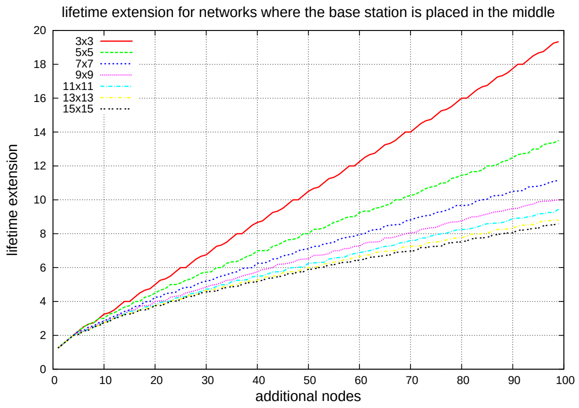

Fig. 4. Lifetime improvement for sensor networks where the base station is placed in the center of the grid.

Figures 5 and 6 show the results. Compared to the previous figures, the overall lifetime increase is much lower, in particular for the rectangular network. The reason for this is presented in Table 2 which shows that the lifetime extension depends heavily on the number of nodes already present in the spheres close to the base station. For the grid networks only a small fraction of the nodes are in these inner spheres while in the random networks there is already a large number of nodes in these spheres. Therefore, the gain of adding additional nodes is lower for the random networks.

Network type	nodes in S_1	nodes in S_2	nodes in S_1 and S_2	gain with 16 add. notes
Grid with BS in corner, Fig 1	2	3	5%	3.7
Grid with BS in middle, Fig 2	4	8	12%	3.5
Random circular, tr. 3	6	16	22%	3.0
Random circular, tr. 4	12	33.5	45.4%	2.4
Random rectangular, tr. 2.5	11.5	17.5	19%	2.1
Random rectangular, tr. 4	24.1	44.9	69%	1.7

Table 2. Impact of the number of nodes in the inner spheres on the lifetime extension achievable by adding additional nodes.

4 Related Work

There are different approaches to overcome the *hot spot* problem in wireless sensor networks. Data aggregation, that we do not consider here, and distributed context decision as proposed by Ahn and Kim [1] are only two examples. As in our lifetime model, Sichitiu et al. divide a sensor network into spheres [10]. While we increase the lifetime of the

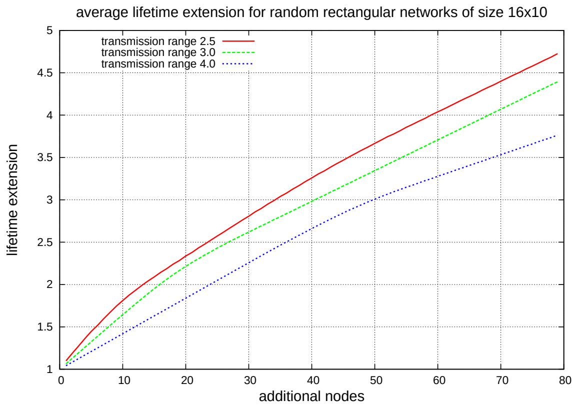

Fig. 5. Lifetime improvement for random rectangular sensor networks size 16×10

network by distributing additional nodes and hence additional energy, they increase the network's lifetime by redistributing the total energy budget in multiple battery levels. Perillo et al. have investigated the performance of optimal transmission range distributions but found that even unlimited transmission ranges alone cannot solve the hot spot problem [7]. In another article the same authors state that deploying more nodes around the base station mitigates the hot spot problem but note that doing so is not always feasible when sensors are randomly deployed [8]. While this is true to some extent it is nevertheless possible to impact "random" deployments. Think of sensor nodes that are distributed by throwing them from an aircraft as envisioned by Estrin et al. [5]. If the base station is a dedicated node that is distributed from the aircraft in the same way as all other nodes, the node density around the base station can be increased by simply throwing out an above-average number of nodes together with the base station.

Other strategies to mitigate the hot spot problem include the notion of multiple or moving base stations [6] as well as data aggregation and clustering.

5 Conclusions

The hot spot problem in wireless sensor networks is caused by the fact that the sensor nodes around the base station need to forward more packets to the base station than other nodes. Therefore, these nodes potentially run out of energy first forming a critical area. Since it is generally assumed that sensor nodes will become inexpensive a simple solution to this problem is to add supplementary nodes in the hot spot area. Using a mathematical model we have shown that for some networks adding only a limited number of nodes can drastically increase the lifetime of the sensor network. The possible lifetime gains depend very much on the proportion of nodes already present in the area around the base station.

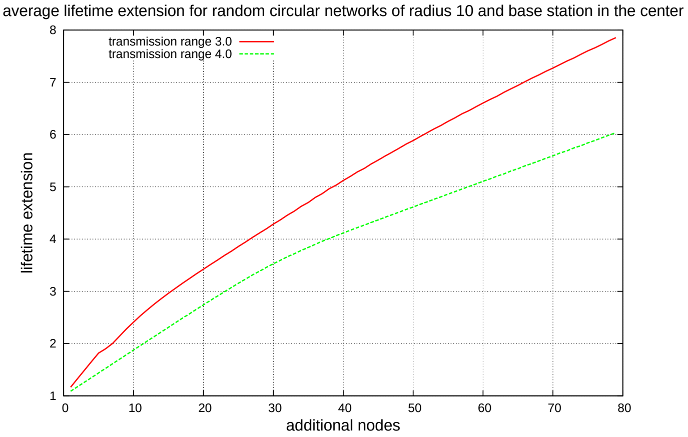

Fig. 6. Lifetime improvement for random circular sensor networks of radius 10

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