Base Station Location *Optimization for Wireless Sensor Networks*

EHM4260 Project – Alirıza Bilir-18014125

Abstract

Wireless sensor networks (WSNs) have gained significant attention over the past decade. These networks comprise multiple sensor nodes that gather data and relay it to one or more base stations. Sensor nodes typically operate on batteries, making energy a limited resource for them.

The energy consumption of a sensor node is largely dependent on the communication distance, with energy usage increasing exponentially as the distance grows. When sensor nodes transmit their data directly to the base station, those situated farther away tend to deplete their energy rapidly. Conversely, if each node forwards its data to the nearest sensor node on the path to the base station, the nodes closer to the base station exhaust their energy more quickly.

Hence, balancing the flow of data within the network is crucial. In this study, we investigate the impact of optimizing the base station's location along with balancing the data flow. To achieve this, we compare different localization methods applied to various network topologies.[1]

Introduction

Wireless sensor networks (WSNs), originally conceived for military purposes, have gained prominence across various spheres of human life. The nodes in a WSN consist of sensors capable of gathering information in their vicinity and transmitting it to a base station without physical connections. This characteristic enables WSNs to be easily deployed in hazardous or inaccessible areas, providing essential information such as humidity, temperature, pesticide concentration, noise, etc. Consequently, WSNs find applications in diverse fields including environmental monitoring, healthcare, military operations, industrial setups, agriculture, and more.

However, a significant drawback of WSNs lies in the operation of sensor nodes with infrequently rechargeable and/or limited energy resources like batteries, gradually depleting over time. When a sensor node exhausts its energy source, it becomes non-functional, unable to collect, transmit, or exchange information with the base station, thus impeding the WSN's mission completion. The duration from the initiation of WSN operations to the depletion of the first sensor node's energy is termed as the network lifetime, considered a pivotal measure in evaluating WSN quality. Therefore, a longer network lifetime indicates a better-performing WSN, directly linked to the speed of energy consumption by sensor nodes. Effectively utilizing sensor nodes' energy becomes a paramount concern addressed in this paper, focusing on maximizing the lifetime of WSNs.[2]

Node energy consumption is depicted by the formula shown in Fig. 1, which is dependent on the distance between nodes.

Energy consumption of sensor node i :

$$P_i = \rho \sum_{k\in N}^{k\neq i} W_{ki} + \sum_{j\in N}^{j\neq i} V_{ij} \cdot W_{ij} + V_{iB} \cdot W_{iB}$$

W_{ki} (b/s) : *Bit rate coming from node k to i*

ρ : *Constant coefficient*

Nonlinear function of the base station position

$$V_{ij} = \beta_1 + \beta_2 \cdot d_{ij}^{\alpha} \quad \textit{(Between I and J Nodes)}$$

$$V_{iB} = \beta_1 + \beta_2 \left[\sqrt{(X_B - X_i)^2 + (Y_B - Y_i)^2}\right]^{\alpha} \quad \textit{(Between Base Station and I Nodes)}$$

d_{ij}^{α} : *Distance between nodes*

(X_B, Y_B) : *Base statiton position*

β_1 and β_2 : *Constant parameters*

α : *Path-loss index*

W_{ij} and W_{iB} : *Flow rates*

Fig.1 Energy Consumption Formula for Sensor Nodes

There exist numerous methodologies and approaches to maximize the lifetime of WSNs. Typically, researchers address this issue by considering effective routing methods in data transmission with randomly allocated sensor node locations and the base station. However, optimizing the base station location emerges as a critical aspect in maximizing the lifetime of WSNs, forming the basis of our approach.

The problem of maximizing the lifespan of Wireless Sensor Networks (WSNs) has captured significant attention among researchers. According to the literature [3], there are two primary approaches to enhance network lifespan: one focuses on minimizing energy consumption, while the other directly aims to maximize the network's longevity.

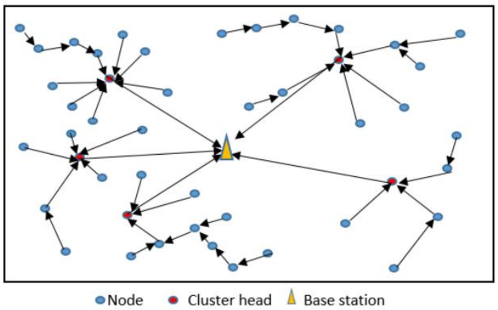


Fig.2 Network Model [4]

Optimization Methods

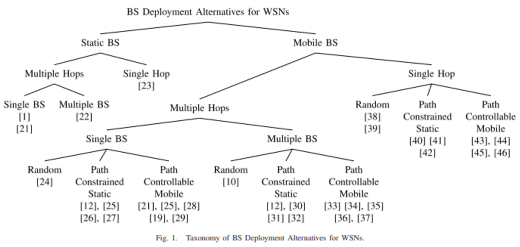


Fig.3 Location Optimization Methods [5]

There are numerous optimization methods used to determine the location of the base station, as illustrated in Figure 3. Several of these methods will be detailed to provide a comprehensive comparison in the comparison section.

To maximize the lifetime of WSNs, the location of the base station should not only be close, but also maintain balanced distances with as many sensor nodes as possible. This ensures that the sensor nodes do not consume excessive energy when transmitting data to the base station and prevents any one node from consuming its energy significantly faster than the others. Although the center of the network seems to fulfil this requirement, different definitions provide different locations. This paper will describe 4 popular optimization methods for the types of positioning given in figure 3, and the discussion will comment on all optimizations in general. The 4 methods to be described are:

Centroid Method

We start being defining the notion of geometric centroids and then analyze the performance bounds of single-hop communication backbone which is centroid-based. In the end we discuss the possible pitfalls of using a single-hop collection tree. For n points

$$P = \{p1, p2, \dots, pn\}, n \geq 2,$$

placed in the Euclidean plane, with coordinates $(xi, yi), i = 1, \dots, n,$ and assuming general position, the centroid $c(P)$ is a point defined as $c(P) = (x, y),$ where $x = \sum n\ i = 1\ xi/n\ and\ y = \sum n\ i = 1\ yi/n,$ which conceptually represents the center location of P. Apparently, the centroid of n points has two very interesting properties as outlined in the following theorems that provide an analysis of the sum of squares of distances, which was done in [6], and sum of distances, which we develop here, between the points and the centroid.[7]

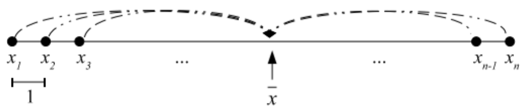


Fig.4 Center of x Coordinates [7]

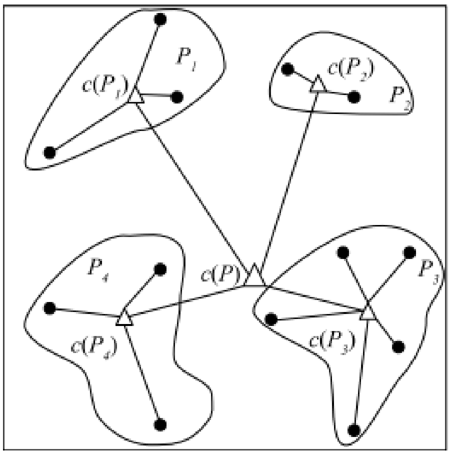


Fig.5 c(P): Centroid of Nodes [7]

Smallest Total Distances Method

The proposed algorithm is developed to determine the optimal location by considering the distance factor between sensor nodes and virtual base station locations. This algorithm involves a set of live sensor nodes (N) and a set of virtual base station locations (V). The optimal location (v*) is chosen from the set of virtual locations, calculating the distances between sensor nodes and virtual locations to make this selection. Each virtual location's total distance from live sensor nodes is defined by a weight function (Wj). The virtual location that provides the smallest total distance to live sensor nodes is identified as the optimal base station location.[8]

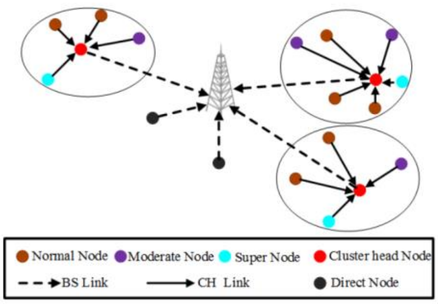


Fig.6 Network Model of Formulas [8]

α can be calculated by using the equation below

$$\alpha = (\frac{M}{D} - 1)^2$$

The distance between each i and j is given by

$$d(i,j) = \sqrt{[(x_i - x_j)^2 + (y_i - y_j)^2]}$$

The distance between virtual location j and alive sensor nodes N is defined as a weight function Wj as follows

$$W_j = \sum_{i=1}^{n} d(i,j)$$

*From calculated weights, the location that provides the smallest distance from all alive sensor nodes is the optimal BS location, which is given as v**

$$v^* = \arg\min(W_j)$$

Alive Sensor Nodes

$$N=\{i|1 \le i \le n\}$$

BS virtual locations

$$V=\{j|1 \le j \le v\}$$

v^* *: Optimal Location*

(x_i, y_i) *: Coordinates of sensor node i*

(x_j, y_j) *: Coordinates of the virtual location j*

D *: distance between neighboring virtual locations in the grid*

α *: number of virtual locations*

Fig.7 Example Formulas of STDM Optimization [8]

Smallest Total Squared Distances Method

Grid-based clustering is a clustering technique that divides networks into equally sized square grids, presenting a straightforward structure where all nodes within the same grid are equivalent from a routing perspective. With the aid of GPS or localization techniques, it offers easier coordination among all sensor nodes in the grid-based network, making it useful enough to incorporate all significant aspects of a network while allowing for theoretical analysis. Moreover, it significantly simplifies the data dissemination process, enabling sensor nodes to transmit data without explicitly setting up a routing path after sensing data. This allows for rapid data propagation without additional overhead of routing construction or maintenance, which is beneficial for real-time applications. In this study, two routing schemes, Diagonal-First routing, and Manhattan Walk, used to achieve one-time communication between clusters, are examined. In Manhattan Walk, the grid size "s" is selected so that any two nodes in horizontally or vertically adjacent grids are within the maximum transmission range "r" of each other, meaning "s ≤ r/√5". Diagonal-First routing, on the other hand, divides the network into smaller grids, "s ≤ r/√8", allowing nodes in diagonal grids to be within the same transmission range. The performance of these two routing schemes will continue to be analyzed based on distance distributions.[9]

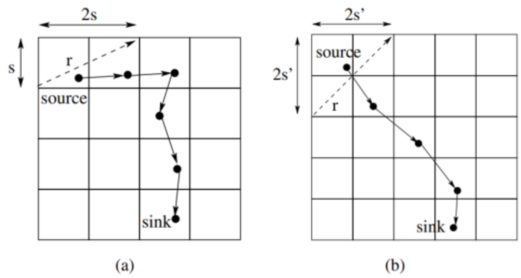
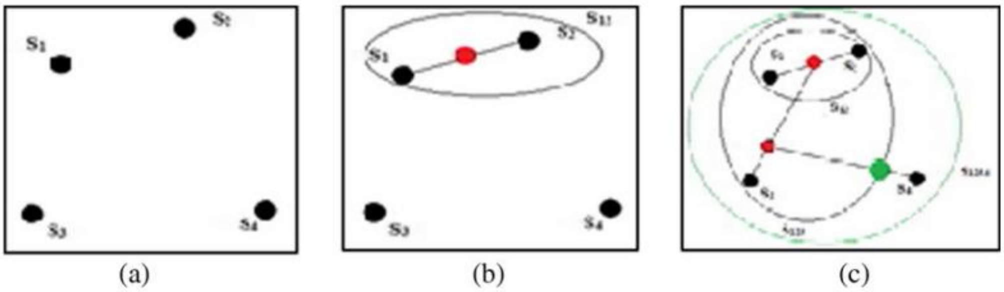


Fig.8 Manhattan Walk and Diagonal-First Routing.[9]

Greedy Method

Defines a sensor set includes sensor nodes and a delegate center. If the set has only one sensor node, its delegate center is this own sensor node. Also, we define the distance between two sensor sets is the distance between their two delegate centers. The main idea of this method is that starting with one-sensor-node sets (Fig. 1a), we merge two sets having the smallest distance (sensor node set S1 and S2 in Fig. 1a). A new delegate center for the merged set (the red node in Fig. 1b) is specified as follows: this center is on the line segment connecting two old delegate centers and splits this line into two segments proportional by p. The sensor sets are merged until only one set remains. The delegate Fig. 9 Illustration of the greedy method center of this last set is the base station location (The green node in Fig. 1c). [10-12]

Fig.9 Greedy Algorithm [13]



Lifetime Simulations

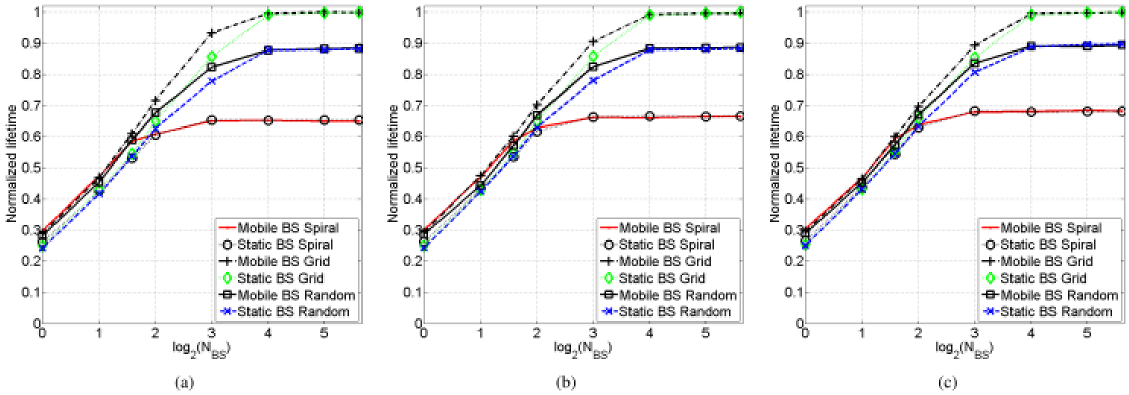


Fig.10 Simulation Results [14]

Figure 9 shows the results of the simulations carried out in areas of different sizes. These simulation results clearly show that grid-based optimizations are the option that increases the lifetime the most. [14-15]

Conclusion

In conclusion, Grid-based base station location optimization plays an important role in improving the performance of wireless sensor networks. These optimizations increase energy efficiency and reduce communication costs by extending the lifetime of the network. However, different optimization techniques affect the topology of the network, energy consumption and communication efficiency differently.

The centroid method finds the geometric center of the network and places the base station at this point. This approach usually produces a balanced communication path, but the actual efficiency of the base station may vary depending on the distribution of nodes. The closest distance method takes into account the minimum distance of the base station to the nodes. In this method, the base station is located closer to the nodes, but the load on the base station may increase. The nearest quadrature placement method minimizes the sum of the squares of the distances of the nodes to each other. This approach allows the base station to be more centrally located while reducing energy consumption.

The Greedy method tries to determine the center of the network by combining sensor nodes according to their distance from the base station. This method aims to distribute energy consumption in a balanced way while considering all nodes of the network. However, in the process of aggregating and combining nodes, some nodes may consume more energy or experience communication problems. Each of these optimization methods can be advantageous in certain scenarios, while in other cases they may bring some limitations. Therefore, it is important to choose the optimization method according to the specific requirements and topology of the network.

In this paper, the location optimization methods of base stations of wireless sensor networks are examined and explained in terms of lifetime. However, if there are different conditions, for example, for the network to work with minimum error, different methods should be examined and compared.

References

[1] - Hakan Ezgi Kızılöz, "On Base Station Localization in Wireless Sensor Networks," Balkan journal of electrical & computer engineering, vol. 8, no. 1, pp. 57–61, Jan. 2020, doi: https://doi.org/10.17694/bajece.613154.

[2] - Y. Gu, M. Pan and W. W. Li, "Prolonging the Lifetime of Large Scale Wireless Sensor Networks via Base Station Placement," 2013 IEEE 78th Vehicular Technology Conference (VTC Fall), Las Vegas, NV, USA, 2013, pp. 1-5, doi: 10.1109/VTCFall.2013.6692379.

[3] - Qunfeng D (2005) Maximizing system lifetime in wireless sensor networks. In: Information processing in sensor networks. 13–19

[4] - Optimal Base Station Location for Network Lifetime Maximization in Wireless Sensor Network," Sandrine Mukase, Kewen Xia, Abubakar Umar ResearchGate, 2021, doi: https://doi.org/10.3390//electronics10222760.

[5] - O. Cayirpunar, B. Tavli, E. Kadioglu-Urtis and S. Uludag, "Optimal Mobility Patterns of Multiple Base Stations for Wireless Sensor Network Lifetime Maximization," in IEEE Sensors Journal, vol. 17, no. 21, pp. 7177-7188, 1 Nov.1, 2017, doi: 10.1109/JSEN.2017.2747499.

[6] - A. Kumar, Y. Sabharwal, and S. Sen. Linear-time approximation schemes for clustering problems in any dimensions. Journal of the ACM, 57(2):1–32, 2010.

[7] - "Location, location, location: Using central nodes for efficient data collection in WSNs," Ieee.org, 2013. https://ieeexplore.ieee.org/document/6576452 (accessed Dec. 14, 2023).

[8] - S. S. A. Abbas, T. Dag and T. Gucluoglu, "Increasing Energy Efficiency of WSNs Through Optimization of Mobile Base Station Locations," 2021 29th Signal Processing and Communications Applications Conference (SIU), Istanbul, Turkey, 2021, pp. 1-4, doi: 10.1109/SIU53274.2021.9478007.

[9] - Y. Zhuang, J. Pan and L. Cai, "Minimizing Energy Consumption with Probabilistic Distance Models in Wireless Sensor Networks," 2010 Proceedings IEEE INFOCOM, San Diego, CA, USA, 2010, pp.19,doi:10.1109/INFCOM.2010.5462073.

[10] – Paschalidis IC, Wu R (2012) Robust maximum lifetime routing and energy allocation in wireless sensor networks. In: International Journal of Distributed Sensor Networks, vol. 2012, (Article ID 523787):14

[11] – Nama H, Mandayam N (2005) Sensor networks over information fields: optimal energy and node distributions. In Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC'05), vol. 3:1842–1847

[12] - Li Y, Xiao G, Singh G, Gupta R (2013) Algorithms for finding best location of cluster heads for minimizing energy comsumption in wireless sensor networks. In: Wireless Network, vol. 19, (issue 7): 1755–1768

[13] - Nguyễn Thanh Tùng and T. Bình, "Base Station Location -Aware Optimization Model of the Lifetime of Wireless Sensor Networks," Mobile Networks and Applications, vol. 21, no. 1, pp. 10–17, May 2015, doi: https://doi.org/10.1007/s11036-015-0614-3.

[14] - O. Cayirpunar, B. Tavli, E. Kadioglu-Urtis and S. Uludag, "Optimal Mobility Patterns of Multiple Base Stations for Wireless Sensor Network Lifetime Maximization," in IEEE Sensors Journal, vol. 17, no. 21, pp. 7177-7188, 1 Nov.1, 2017, doi: 10.1109/JSEN.2017.2747499.

[15] - A Comparative Study and Analysis of Data Aggregation Techniques in WSN | Request PDF," ResearchGate, 2015, doi: https://doi.org/10.17485//ijst//2015//v8i26//81713.