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Maximizing Wireless Sensor Network Lifetime With Energy Efficiency And Load Balancing

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Abstract:
In the world of wireless sensor networks, two essential limits stand out as the most significant: transmission range and energy source constraints. These elements are critical to maximizing the longevity of sensor networks. A full evaluation of their performance is based on a number of parameters, including data transfer capacity, transmission strategy, and network longevity. Analytically, these factors are extremely important, especially in defining favourable design solutions. Exploring the limitations of these parameters allows us to successfully handle the network maximization challenge. Other network factors, such as beginning energy, number of sensor nodes, and operating area, as well as network management features such as routing, energy optimization, and topology, are also important in evaluating network optimization.
These concerns are fundamental in both hypothetical and real-world wireless sensor network studies. They provide useful information for network scalability, feasibility, and performance evaluation. We suggest using the most favorable distance (MFD) strategy to maximize energy efficiency and limit energy depletion while encouraging network lifetime maximization. To do this, we present a heuristic ACO (Ant Colony Optimization) technique. To discover the shortest path probabilistically, this algorithm integrates control parameters (alpha, beta), evaporation rate, heuristic information, and pheromone updates. We can efficiently optimize energy balance and increase the network's lifetime by adopting this strategy. We conducted experiments in the MATLAB environment to validate the proposed methodology, taking into account both theoretical and mathematical aspects. The collected

findings demonstrate the efficacy and efficiency of our strategy for maximizing network lifetime while optimizing energy use.

Keywords: Wireless Sensor Networks, Transmission Range, Network Lifetime, Data Transmission Capacity, Most Favourable Distances (MFD) , Heuristic ACO, Energy Efficiency.

1. Introduction

It is vital to prioritize sensor energy savings in order to improve network durability when operating Wireless Sensor Networks (WSNs) [1, 2, & 3], as information transmission from sources to a central sink is critical. Transmission and traffic management systems must be optimized to ensure energy efficiency, load-traffic equilibrium, and extended network lifetime. The network's geographical dimensions and coverage area are critical, with traffic being more concentrated near the sink than in the network's farthest reaches. As a result, these factors have a major impact on the overall network lifetime. Previous attempts to solve these issues used a variety of passive strategies.

The Single-Hop (SH) direct transmission system [4], the Multi-Hop (MH) with set transmission distances [4], and a hybrid combination of both (SH and MH) [5] are among the proposed ways. In addition, to handle network load, energy usage, and packet collisions, the clustered-based Low-Energy Adaptive Hierarchy (LEACH) algorithm [6] has been introduced. The selection of a secondary cluster leader based on residual power and minimal average variations is included in the process to optimize load distribution, thereby improving network efficiency and lifetime.

Furthermore, the Hybrid Energy Efficient Distributed (HEED) protocol [7] solves the clustering problem using a hybrid methodology that takes into account node residual energy as well as proximity to neighbors and the sink. Data aggregation is used to increase network longevity. The Ant Colony Optimization (ACO) algorithm has been modified to overcome these issues. The Energy Aware ACO Protocol (EAACA) [8] includes nodal average energy and residual energy into the transmission process to accomplish this. The ACO Dynamic Routing Protocol (DRRP) [9] uses node energy levels to dynamically build trails. Furthermore, the Energy Efficient Ant-Based Routing (EEABR) algorithm [10] optimizes route building by taking advantage of pheromone likelihood for forward and backward trail formation.

Despite their efficiency, passive approaches fall behind in traffic management strategies. Distances between source and sink nodes, transmission range, and traffic are all important factors to consider while addressing network longevity. As a result, our suggested methodology focuses on Energy efficiency, nodal energy usage, and traffic balancing via an energy strategy that is both efficient and balanced, ultimately boosting network lifetime.

The following is how the paper is organized: The developed algorithm is explained and its flow is shown in Section 2. Section 3 contains mathematical modeling and associated formulas. The results are validated in Section 4 using the MATLAB environment. Finally, Section 5 concludes the work and discusses future aspects..

2. Developed Algorithm and Workflow

Figure 1 depicts a network model that resembles a disk with radius R. The network is made up of nodes with equal density and limited energy, while a single centrally positioned sink has enough energy. The model is divided into N unconnected concentric coronas with w = R/N widths. Furthermore, the angle divides the entire region into sectors labeled Si, S2,..., SN [11, 12 & 13].

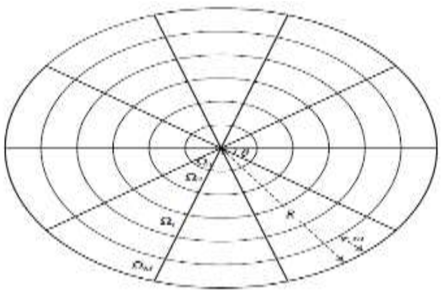


Figure 1: Network Model

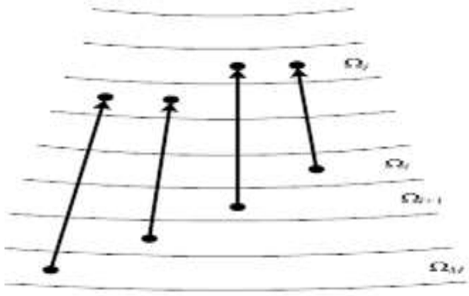


Figure 2.Routing Abstraction

We propose a distributed network system with nodes dispersed uniformly across a defined area. Each node has an initial energy capacity that allows it to generate and transport data. The network is comprised of a permanent sink with adequate power at its heart and several stationary nodes with limited battery life. The nodes were originally classified into K levels depending on their maximal transmission range, with each level representing a different corona thickness.

We introduce the idea of self-generated data volume, which is considered to be consistent across all sectors, to improve energy utilization. An ant is placed in each sector, and its movement is guided by a probability distribution (Figure 2). The ants' movement begins with the farthest ant and continues until the final one moves. The ideal transmission distance for energy-efficient data transfer is estimated throughout their travel to reduce overall energy usage.

We analyze paths with a distance d of x hops between transmitters and receivers to create effective communication paths. The use of a multi-hop method

considerably reduces energy consumption per hop. We calculate the best efficient energy distance (BEED) and the best balanced energy distance (BBED) for each sector, with the goal of minimizing the overall energy consumption along the transmission line. Every node within the same sector uses the same transmission distance to provide balanced energy distribution. Total data volume is calculated by adding self-generated and received data volumes. In addition, for each sector, we calculate the average energy consumption per node (ECPN). We introduce pheromone intensity on each path to optimize path selection, which is updated after each iteration.
Our goal is to determine the ideal path that lowers the maximum average ECPN while also maximizing network longevity. This method ensures that energy is used efficiently and in a balanced manner throughout the network, extending its operational life. Please refer to the workflow diagram (Figure 3) for a thorough grasp of our recommended methodology.

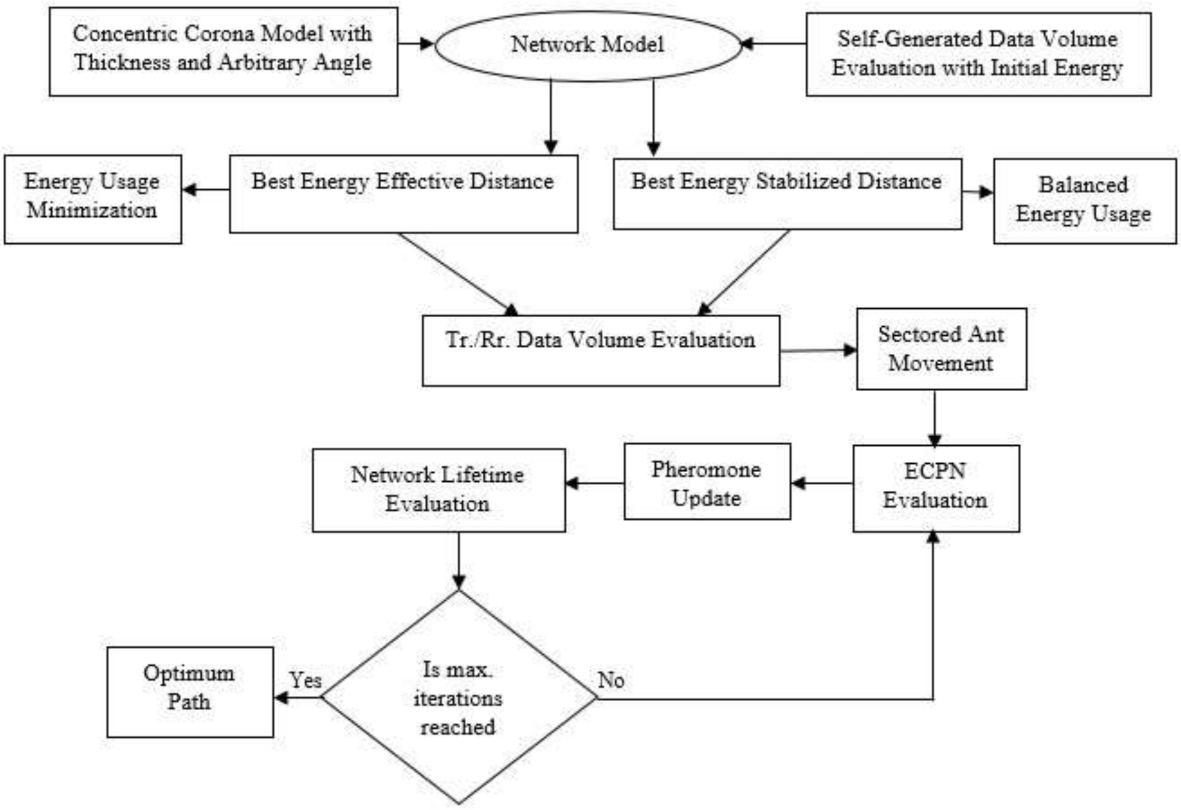


Figure3: Work Flow

3. Mathematical Modelling

The initial data volume Ξi [11] is associated with each node and is defined by its starting energy Ɛ0 and data rate (measured in bits per second) for a sector [12].

$$\Xi_i = \phi \cdot \sigma \cdot \frac{\theta}{2\pi}\left\{\pi(i\omega)^2 - \pi[(i-1)\omega]^2\right\}$$

(1)

assumed initial nodal energy and transmission range level K, the value of which is set to corona width ω . The transmitting and receiving communication approaches (Figure 4), with data rate mbits for a distance d, path loss, and energy consumed in transmit electronics and amplifiers, respectively, are elec and amp, Ɛamp and the related energy consumption formulae are [11, 14 & 15]:

$$E_{Tx}(m,d) = m\varepsilon_{elec} + m\varepsilon_{amp}d^{\gamma}$$

(2)

$$E_{Rx}(m) = m\varepsilon_{elec}$$

(3)

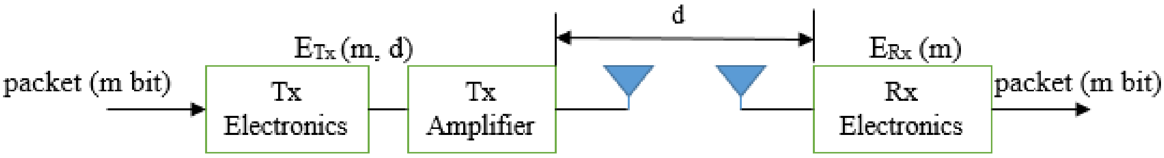


Figure 4: Communication Model

Ant motions in sectors Si to Sj form a trail T (i, j) with a distance given by:

$$d_{ij} = (i - j)\omega$$

(4)

The transmission path between nodes corresponding to sectors Si and Sj is represented by trail T (i, j). dij represents the distance between these nodes. The most efficient path is selected by a series of specified iterations that include path updates and reservations.

The overall volume of transmitted data Vi in the routing abstraction from sector Si to sink is determined as the sum of self-produced data Ξi and incoming data arriving at its end Φi.

$$V_i = \Xi_i + \Phi_i$$

(5)

The received data volume for Sector Sj will be calculated as follows:

$$\Phi_j = \sum_{S_i \in DIS_j} \Xi_i$$

(6)

Let DIS $_j$ represent the sector of direct informants. Using equations (2) and (3), the average value of the energy consumption per node (ECPN) required for sector communication Si may be calculated:

$$\overline{E_i} = \frac{E_{Rx}(\Phi_i) + E_{Tx}(\Xi_i, d_{ij})}{C_i}$$

(7)

$$\overline{E_i} = \frac{\Phi_i \varepsilon_{elec} + (\Phi_i + \Xi_i)\varepsilon_{elec} + (\Phi_i + \Xi_i)\varepsilon_{amp}[(i-j)\omega]^{\gamma}}{C_i}$$

(8)

Where Ci denotes the number of sectored nodes.
As a result, the Best Effective Energy Distance (BEED) and Best Balanced Energy Distance (BBED) [11] are as follows:

$$d = \sqrt[\gamma]{\frac{2\varepsilon_{elec}}{(\gamma - 1)\varepsilon_{amp}}}$$

(9)

$$d_{ij} = \sqrt[\gamma]{\frac{C_i \vartheta - (2\Phi_i + \Xi_i)\varepsilon_{elec}}{(\Phi_i + \Xi_i)\varepsilon_{amp}}}$$

(10)

Where ϑ denotes Energy use at nodes in each sector and is provided by:

$$\vartheta = \frac{\Phi_i \varepsilon_{elec} + (\Phi_i + \Xi_i)\varepsilon_{elec} + (\Phi_i + \Xi_i)\varepsilon_{amp} d_{ij}^{\gamma}}{C_i}$$

(11)

ACO (Ant Colony Optimization) [16] is a technique that uses heuristic information [17], pheromone intensity, and transition probability to find the best routing abstraction. Pheromones and heuristics are associated with the volume of data and transmission range of the method. After the sixth iteration, an ant's transition probability for traveling from sector Si to sector Sj is stated as follows:

$$\mathrm{P}_{ij}(t) = \frac{[\mathrm{I}_{ij}(t)]^{\alpha}[\mathrm{H}_{ij}(t)]^{\beta}}{\sum_{S_r \in DIS_j}[\mathrm{I}_{ij}(t)]^{\alpha}[\mathrm{H}_{ij}(t)]^{\beta}}$$

(12)

The pheromone concentration and the heuristic information of the trail T(i, j) are represented by the factors Iij(t) and Hij(t), respectively. Constants are the control factors that determine how pheromones and heuristics influence ant movement decisions. Within sector Si, DISi indicates the set of candidate informative sectors..

4. Result Validations

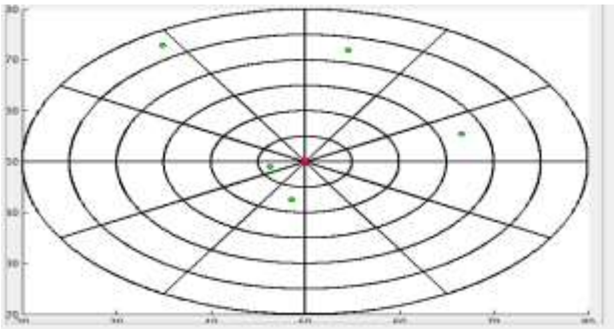
The simulated results are displayed in the following sections and subsections in the MATLAB environment: The simulations of the system use a variety of parametric settings, which are included in Table 1 for reference.

Table 1: Network and System Parameters

Sl. No.	Parameters	Values
1	Radius (R)	20-200 m
2	No. of Nodes	100
3	No. of Ants	10
4	Corona Width (w)	6m
5	Angle theta (Θ)	π/6
6	Node Density (σ)	5
7	Initial energy ($\mathcal{E}_0$)	10 J
8	Energy Consumption by transmitter circuitry(e_{elec})	40nJ/bit
9	Energy Consumption by Amplifier (ε_{amp})	13pJ/bit/m^2
10	Data Rate (l bits/sec)	256
11	Path Loss (γ)	2
12	Energy efficiency factor (Ψ_1)	3
13	Energy balancing factor (Ψ_2)	4
14	Constant (λ)	2
15	Magnitude factor (μ)	10^{-4}
16	Evaporation Rate (ρ)	0.05
17	Control Parameters (α, β)	5
18	Transmission Range Energy Level (K)	5 - 12

4.1: Simulated Network Model

The network model shown in Figure 5 is divided into six sectors. This model is the foundation for all the following results. Figure 5 (a) depicts manual node placements, which show nodes that have been manually positioned. The initial ant movement is depicted in Figure 5 (b), utilizing the farthest movement first technique. Figure 5 (c) depicts the last hop movement technique used. Figure 5 (d) depicts a typical final optimum path, which represents a specific energy level with the lowest maximum average nodal energy consumption (ECPN). The ideal path is defined by the average (mean) value of the maximum ECPN, and the lower the value, the longer the system's lifetime. Figure 5 (d) in particular shows a nearly balanced course.



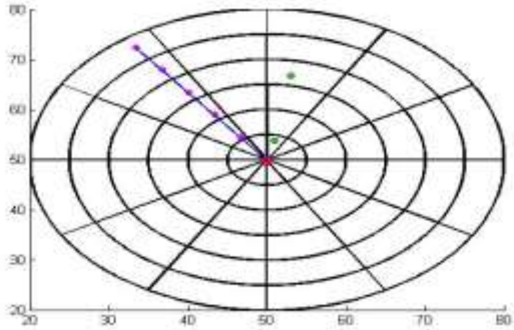
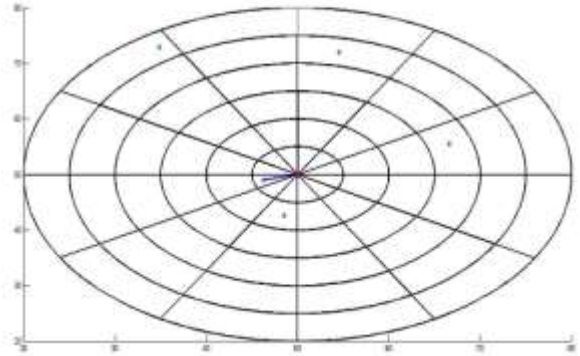
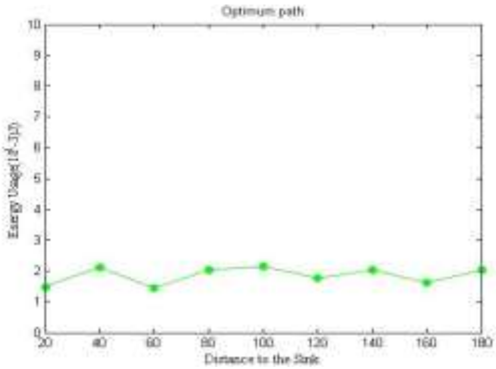


Figure5: (a) Sample Manual Node Deployment (b) Initial Ant Movement (Most Outer Sector First)





(c) Last Hop Final Ant Movement (d) Optimum path

4.2: Distance Estimations

Table 2 shows the simulated best efficient energy distance (BEED) and best balanced energy distance (BBED) values for each sector. These lengths were derived through simulations based on the modelling equations mentioned in Section 3 in order to reduce total energy consumption during transmission. Following this course will result in lower overall energy consumption, which will increase network lifetime.

Table 2: Best efficient and balanced distances for 6 sectors

Best Energy Efficient Distance (BEED)	Best Balanced Energy Distance (BBED)						
		1	2	3	4	5	6
3.16228	1	5.4772	7.4162	8.9443	10.2470	11.4018	12.4499
	2	2.3905	6.7082	9.1807	11.1163	12.7615	14.2177
	3	5.7035i	3.3832	7.4446	9.9698	11.9739	13.6876
	4	8.5699i	5.2374i	4.3107	8.0371	10.5170	12.5148
	5	10.7382i	8.2589i	4.5946i	5.0980	8.5492	10.9631
	6	27.9285	28.3725	28.8097	29.2404	29.6648	30.0832

4.3: Data Volume Estimations

As indicated in section 3, the total data volume is computed by combining sectored self-generated data volume with received data volume. Table 3 depicts the simulated total data volume values.

Table 3: Total Data Volume for 6 sectors

	1	2	3	4	5	6
1	0	0	0	0	0	0
2	4.7124e+05	8.2467e+05	1.0865e+06	1.2926e+06	1.4623e+06	1.4399e+05
3	9.4248e+05	1.6493e+06	2.1729e+06	2.5853e+06	2.9246e+06	2.8798e+05
4	1.4137e+06	2.4740e+06	3.2594e+06	3.8779e+06	4.3868e+06	4.3197e+05
5	1.8850e+06	3.2987e+06	4.3459e+06	5.1705e+06	5.8491e+06	5.7596e+05
6	2.3562e+06	4.1233e+06	5.4323e+06	6.4632e+06	7.3114e+06	7.1995e+05
7	2.8274e+06	4.9480e+06	6.5188e+06	7.7558e+06	8.7737e+06	8.6394e+05
8	3.2987e+06	5.7727e+06	7.6053e+06	9.0484e+06	1.0236e+07	1.0079e+06
9	3.7699e+06	6.5973e+06	8.6917e+06	1.0341e+07	1.1698e+07	1.1519e+06
10	4.2412e+06	7.4220e+06	9.7782e+06	1.1634e+07	1.3161e+07	1.2959e+06
11	4.7124e+06	8.2467e+06	1.0865e+07	1.2926e+07	1.4623e+07	1.4399e+06
12	5.1836e+06	9.0713e+06	1.1951e+07	1.4219e+07	1.6085e+07	1.5839e+06
13	5.6549e+06	9.8960e+06	1.3038e+07	1.5512e+07	1.7547e+07	1.7279e+06

4.4: Energy consumption per node (ECPN) of Sector and Network Lifetime.

ACO (Ant Colony Optimization) works by combining transition probabilities tied to pheromone strength and heuristic values to determine the best path. For each sector, the simulation calculates the average energy consumption per node (ECPN). A lower ECPN means that the network will be operational for a longer period of time. Table 4 shows the simulated values of average ECPN at various energy levels with respect to sink distances, whereas Table 5 shows the network lifetime in relation to the network radius. Table 5 clearly shows that a wider network radius results in a lower network lifetime. PNAEC (Per Node Average Energy Consumption) is an important indicator for assessing the system's energy efficiency.

Table 4: Average Energy Consumption/node (ECPN) of a Sector

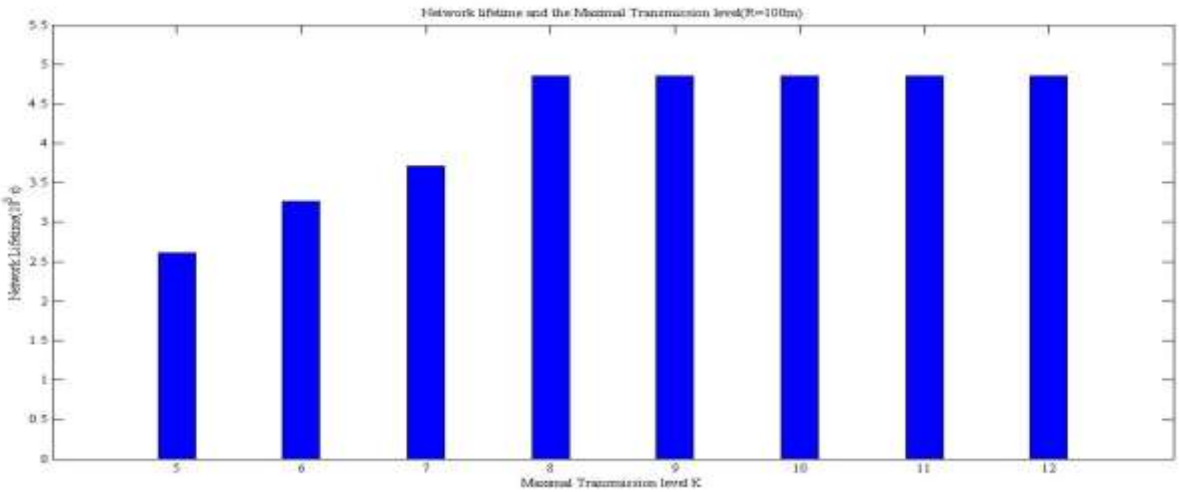
Sl. No.	Distance to the Sink in meters	Energy Levels	
		K=6	K=8
1	20	1.4860	2.2514
2	40	2.1062	2.0403
3	60	1.4499	1.4897
4	80	2.0328	1.9857
5	100	2.1427	1.4620
6	120	1.7792	1.6861
7	140	2.0223	1.5920
8	160	1.6371	1.7944
9	180	2.0212	2.0779

Table 5: Network Lifetime

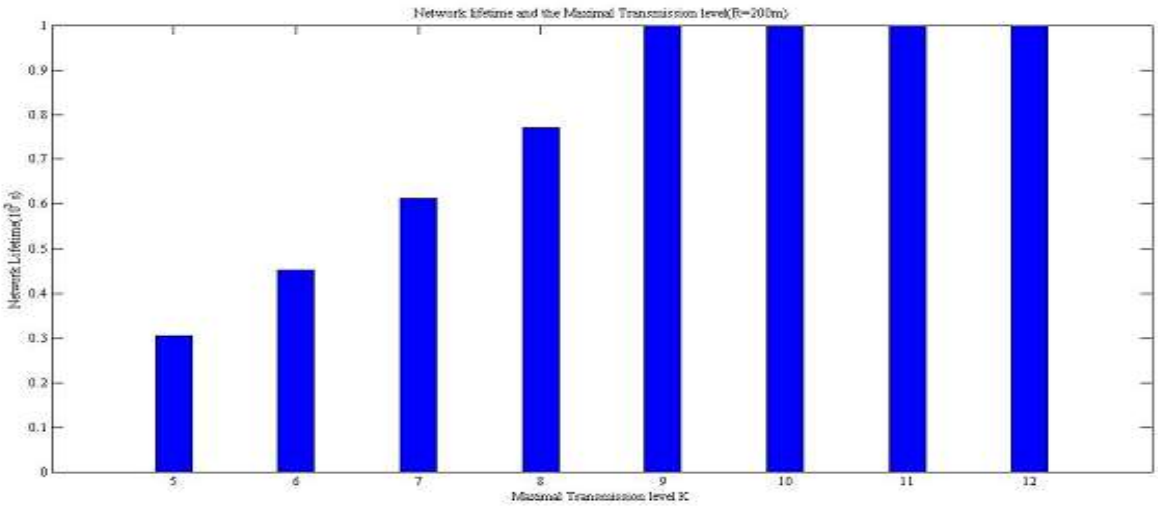
Sl. No.	Network Radius in meters										
	100	110	120	130	140	150	160	170	180	190	200
1	8.5433	6.9532	6.0355	4.6554	3.7986	3.1537	3.1476	2.9733	2.6577	2.5843	2.3203

4.5: Transmission Level K Vs. Network Lifetime

Figure 7 shows how the maximum transmission level, indicated as K, affects the lifetime of the proposed method. A higher K value increases efficiency and energy balance. However, for some K levels (e.g., K = 8, 9, and 10), the lifetime stabilizes, indicating improved energy efficiency across longer communication distances. The figures also show that as the radius changes, the value of K changes from K = 8 to K = 10, indicating that traffic near the sink increases as the area expands.



(a)



(b)

Figure 6: Simulated Graphs showing relation between Transmission level and Network Lifetime for different radius: (a) R=100m (b) R=200m

4.6: Network Lifetime for Various Radii's.

The graph in Figure 7 depicts the lives of various transmission techniques at varying network radii. The following transmission techniques are compared: Single-Hop (SH) [4], Multi-Hop (MH) [4], Hybrid (a combination of SH and MH) [5], EAACA (Energy Aware ACO algorithm) [8], and the suggested ACO-based Most Favourable Distance (MFD). The graph shows that as the network radius expands, so does the longevity due to the increased traffic load associated with a bigger network area. The proposed MFD approach achieves a network lifetime of around 9.2 x 103 seconds at a network radius of 100 meters, while the others perform at 1.5 x 103 seconds (SH), 2.8 x 103 seconds (MH), 3.2 x 103 seconds (Hybrid), and 3.8 x 103 seconds (EAACA). The recommended technique outperforms the competition greatly. Other transmission techniques' poor performance can be due to factors such as long-distance communication (SH), improper load balancing in MH, and EAACA. The suggested approach, on the other hand, optimizes distances for both energy economy and load balance, resulting in higher performance.

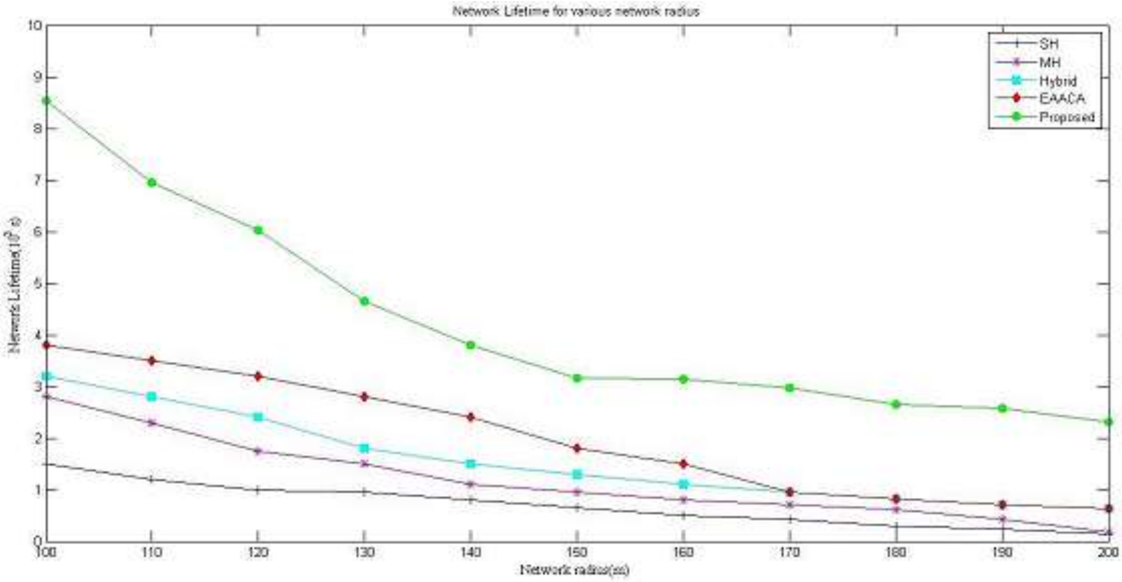


Figure7: Comparative plot for different transmission strategies

5. Conclusion

Wireless sensor networks (WSNs) are critical elements of the Internet of Things (IoT) [18]. However, due to limited energy resources, these networks confront severe hurdles, resulting in rapid energy depletion and shortened network longevity. To overcome this, an ideal communicative abstraction is necessary to maximize energy efficiency while extending the network's lifetime. Energy constraints exist despite the availability of energy harvesting devices such as solar energy [19, 20]. The network's working lifetime reduces as the number of deployed nodes increases. To address this, a very promising distance-based Ant Colony Optimization (ACO) algorithm with Best Efficient Energy Distance (BEED) and Best Balanced Energy distance (BBED) approaches is suggested to achieve great energy efficiency and load balancing.

The ACO algorithm determines the best communication path by taking into account the system model and maximum transmission level. The lifetime of the network may be calculated using the initial energy of each node and the average energy consumption of each sector, as prompted by the updated pheromone intensity. This ensures that ants choose the most effective path with the lowest average energy consumption per node (ECPN) across different sectors, maximizing the lifetime of the WSN. Other techniques, such as SH, MH, Hybrid, and EAACA, which suffer from increasing traffic load with a longer transmission range, are outperformed by the suggested algorithm. The suggested approach, on the other hand, prioritizes lower average maximum energy consumption per node, suggesting the ideal path and resulting in a longer network lifetime.

Further study can build on this work by examining nodal energy distribution throughout the network and considering throughput with both evenly and unevenly distributed nodes.

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