Reliability and Lifetime Maximization of Wireless Sensor Networks: Modelling, Evaluation and Validation

D. Lingamaiah[1*], Dr. D. Krishna Reddy[2], Prof. Perumalla Naveen Kumar[3]

[1*]Ph.D. Scholar, Dept. of ECE., University College of Engineering, Osmania University. Hyderabad-Telangana, India. Email lingam22daggu@gmail.com
[2]Supervisor., Professor & Head., Dept. of ECE., Chaitanya Bharathi Institute of Technology, Hyderabad-Telangana, India. dkrishnareddy_ece@cbit.ac.in.
[3]Co-Supervisor., Professor., Dept. of ECE University College of Engineering, Osmania University. Hyderabad-Telangana, India. naveen.gps@gmail.com

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Abstract
Transmission range and constrained energy sources are the two most important fundamental limitations of sensor networks which evaluates their lifetime. The factors such as data transmission capacity, transmission strategy, and lifetime contribute in evaluating the performance of wireless sensor networks. The number of sensor nodes, area of operation, transmission distances, information routing, energy consumption and network topology are the other factors that define network lifetime. These factors and parameters are analytically important as they become significant towards the most favorable design strategies and they also define the networks scalability, feasibility and reliability. Distances between node to node and node to sink must be optimized to derive maximum network lifetime.The proposed methodology uses the most favorable distances (MFD) approach for energy-efficiency and energy-balance such as to get minimum energy consumption phenomenon leading to network lifetime maximization. A heuristic ACO algorithm which uses control parameters (alpha, beta), evaporation rate, heuristic information, and pheromone updating finds the shortest path on a probability basis. The referred literature is full of such assumptions and algorithms but, this work can be seen as an extension with added simulations. The work presents result validations under MATLAB environment as per the theoretical and mathematical aspects considered. Based upon this an application oriented work is to be carried out and the work will be published in due course of time.
Keywords: Ant Colony Optimization, Energy Consumption, Heuristic Value, Network Lifetime, Pheromone update, Routing Protocols, Transition Probability, WSN

1. Introduction

For efficient running of WSN [1, 2, 3, & 4], energy conservation of sensors is must to achieve better network lifetime since detected information flows from various sources to a sink. The transmission and traffic handling mechanisms are to be handled favorably in order to get energy efficiency, load-traffic balancing and designednetwork lifetime. Distances and area of the network do matter the most as traffic is seen more near to the sink as compared to the farthest part of the network, which is assumed to be playing a pivotal role in deciding the network lifetime. Many passive methods are applied before to address these issues. The Single-Hop (SH), a direct transmission scheme, a Multi-Hop (MH), with fixed transmission distances are presented in [5], a hybrid(SH & MH) form of transmission is studied in [6], clustering based low-energy adaptive hierarchy (LEACH) is presented in [7]. These algorithms are designed by addressing the network load, residual energy and packet collisions. The methodology takes into account secondary cluster head selection using residual energy and minimum average differences thereby distributes the load for better efficiency and lifetime of the network. Addressing the clustering problem, a Hybrid Energy Efficient Distributed (HEED) [8], is presented which uses hybrid methodology comprising nodes residual energy and its closeness with the neighbors and sink. Lifetime is improved by data aggregation. An Energy-Aware ACO protocol (EAACA) is presented in [9], in which the transmission is as per the nodal average energy and nodal residual energy. Ant Colony Optimization (ACO)addresses the multi-objective optimization problem of WSN.Anenergy-level based ACO dynamic routing protocol [DRRP] is presented [10], which dynamically sets a trail using nodes and their energy levels. Energy Efficient Ant Based Routing (EEABR) algorithm [11] establishes forward and backward trails of ants using pheromone probability and sets up an optimized route tree. All these lag the traffic handling mechanisms. The distances between the source node and the sink, transmission range, and traffic matter the most in addressing the network lifetime. The proposed methodology addresses nodal energy consumption, energy efficiency, and traffic balancing through efficient and balanced energy distances and improves the overall network lifetime [2, 4, 12, & 13].

The paper layout is as follows: Section 2 describes the developed algorithm and gives out its flow, Section 3 presents the mathematical modeling with relevant equations, Section 4 validates the results under MATLAB environment and Section 5 concludes the work with a note on future aspects.

2. Developed Algorithm and Workflow

Figure 1 shows a disk shape network model with radius R having uniform nodal density *σ,* nodes with limited energyand a single centered sink with sufficient energy. The model can be seen divided into N disconnected concentric coronas having a width w = R/N. The angle θ can be seen dividing the area into sectors S_i, S_2….S_N [12, 13,& 14].

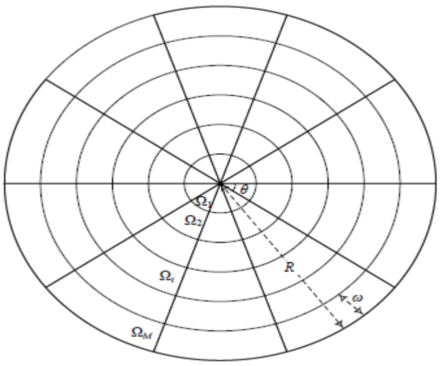


Figure 1: Network Model

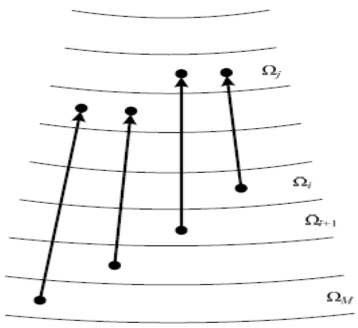


Figure 2. Routing Abstraction

The nodes are uniformly distributed over this area and the nodes are assumed to be having initial energy, generating φ bits of data. A stationary sink with sufficient power is centered on the disk and multiple stationary nodes are located on the network with finite battery power. Nodes are supposed to have initial energy with a maximum transmission range divided into K levels with a unit range corresponding to corona thickness. Self-generated data volume is computed which is assumed to be the same for every sector. An ant is assumed to be placed in every sector and the movement of the ant (Figure 2) is as per a specific probability. The farthest ant moves first and the movement stops with the movement of the last ant's last hop. Every hop's optimal transmission distance is assessed for less energy use overall. Between the transmitter and receiver, a path is established at a distance d of x hops. The overall energy usage will be reduced in each hop. The best efficient-energy distance (BEED), and best balanced-energy distance (BBED) for every sector are estimated for minimizing the total energy usage along the transmission path. If all the nodes use the same transmission distance, then the overall energy usage will be reduced and balanced. Total data volume is estimated which is comprised of self-generated data volume [12] and received data volume [12]. The average value of energy consumption per node (ECPN) [12 & 13] is evaluated for every sector. Pheromone intensity is estimated on every path and it is updated after each iteration. And the final result will be a path having a minimum value of the maximum average value of ECPN which governs the optimal path leading to maximization of network lifetime. The above narratives can be seen in the workflow (Figure 3).

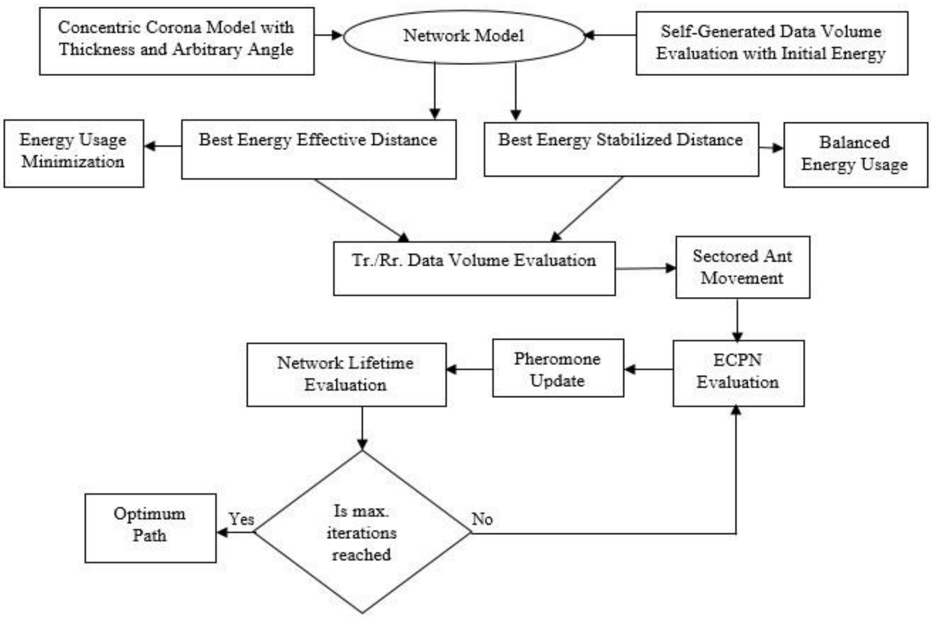


Figure3: Work Flow

3. Mathematical Modelling

The initial data volume Ξ_i[4, 12 & 13] associated with every node having initial energy $\mathcal{E}_0$ and data rate ϕ (bits/sec) for a sector [12& 13] is represented as:

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

Presumptuous initial nodal energy and level K of transmission range, the value of which is set equal to corona width ω. The transmitting and receiving communication approach (Figure 4), with data rate mbits for a distance d, path loss γ, energy consumed in transmit electronics and amplifier respectively are ε_{elec}, $\varepsilon_{amp}$and the respective energy consumption equations are [12, 15 & 16]:

$$E_{Tx}(m,d) = m\varepsilon_{elec} + m\varepsilon_{amp} d^{\gamma} \quad (2)$$

$$E_{Rx}(m) = m\varepsilon_{elec} \quad (3)$$

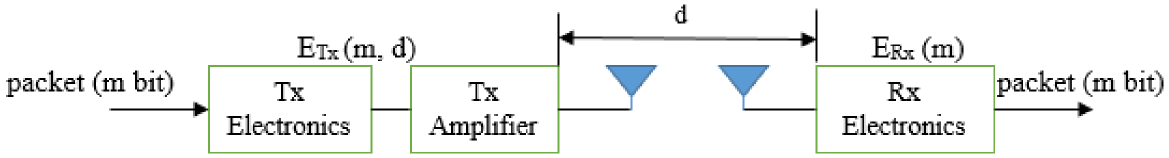


Figure 4: Communication Model

The sectoral movements of ants from $S_i$to $S_j$sets up atrail T (i, j) whose distance is given by:

$$d_{ij} = (i - j)\omega \quad (4)$$

Where, trail T (i, j) is the transmission path and $d_{ij}$is the distance of nodes corresponding to sector S_i. The best route is established after predefined iterations, and is reserved after update.

In the routing abstraction from S_i, $S_j$towards the sink, the total volume of transmitted data V_i, (comprising of sectors self-produced data $\Xi_i$anddata arriving at its end Φ_i) is given as:

$$V_i = \Xi_i + \Phi_i \quad (5)$$

And for sector Sj, the received data volume will be:

$$\Phi_j = \sum_{S_i \in DIS_j} \Xi_i \quad (6)$$

Where, DIS is the Direct informant sector. From, equations (2) and (3), the average value of the energy consumed per node (ECPN) needed for this communication of sector $S_i$is given by:

$$\overline{E_i} = \frac{E_{Rx}(\Phi_i) + E_{Tx}(\Xi_i, d_{ij})}{C_i} \quad (7)$$

$$\overline{E_i} = \frac{\Phi_i \varepsilon_{elec} + (\Phi_i + \Xi_i)\varepsilon_{elec} + (\Phi_i + \Xi_i)\varepsilon_{amp}[(i-j)\omega]^{\gamma}}{C_i} \quad (8)$$

where $C_i$is the sectored node number.

Having assumed the values of ε_{elec}, ε_{amp}, γ, ω, σ, θ, and article [4, 12, & 13] the equation for the best effective-energy distance (BEED) (equation 9) and best balanced-energy distance (BBED) (equation 10) for every sector are given by:

$$d = \sqrt[\gamma]{\frac{2\varepsilon_{elec}}{(\gamma - 1)\varepsilon_{amp}}} \tag{9}$$

$$d_{ij} = \sqrt[\gamma]{\frac{C_i\vartheta - (2\Phi_i + \Xi_i)\varepsilon_{elec}}{(\Phi_i + \Xi_i)\varepsilon_{amp}}} \tag{10}$$

Where, $\boldsymbol{\vartheta}$ is the nodal energy consumption in every sector given by:

$$\vartheta = \frac{\Phi_i\varepsilon_{elec} + (\Phi_i + \Xi_i)\varepsilon_{elec} + (\Phi_i + \Xi_i)\varepsilon_{amp}d_{ij}^{\gamma}}{C_i} \tag{11}$$

ACO [12, 13, &17] utilizes heuristic information [17], pheromone intensity, and probability of transitionto find a best routing abstraction. In the proposed methodology, the pheromone and the heuristics are related to data volume and transmission range. The transition probability of the ant for its movement from sector $S_i$to sector $S_j$afterith iterationis given by:

$$\mathrm{P}_{ij}(t) = \frac{[\mathrm{I}_{ij}(t)]^{\alpha}[\mathrm{H}_{ij}(t)]^{\beta}}{\sum_{S_r \in DIS_j}[\mathrm{I}_{ij}(t)]^{\alpha}[\mathrm{H}_{ij}(t)]^{\beta}} \tag{12}$$

Where, $\mathrm{I}_{ij}(t)$ and $\mathrm{H}_{ij}(t)$ are the factors representing pheromone concentration and the heuristics (visibility) of the trail T(i, j) respectively. α and β are the control parameters and are constants. These control parameters control the effect of the pheromone and the heuristics related to ant movement decision. Considering the best efficient distance, the best-balanced distance controlled by two parameters ψ_1 and ψ_2 respectively, and constants $\lambda_1>0$ and $\lambda_2>0$ that ensures each denominator are not zero, the visibility factor (heuristic value) of the trail d_{ij} from sector Si to Sj *(*from equation 11) is given by [4, 12 & 13]:

$$\mathrm{H}_{ij} = \left[\frac{1}{(d_{ij} - d_{BEED})^{\gamma} + \lambda_1}\right]^{\Psi_1}\left[\frac{1}{(d_{ij} - d_{BBED})^{\gamma} + \lambda_2}\right]^{\Psi_2} \tag{13}$$

The proposed transmission strategy considers the initial energy ε_0, maximal average value of the energy consumed per node (ECPN) to assess network lifetime which is given by (after ithiteration):

$$f(t) = \frac{\varepsilon_0}{\max\{\overline{E_i}(t), i = 1,2,...M\}} \tag{14}$$

The pheromone intensity updating on every trail T (i, j) is governed by:

$$\mathrm{I}_{ij}(t+1) = (1-\rho)\mathrm{I}_{ij}(t) + \Delta\mathrm{I}_{ij}(t) \tag{15}$$

where ρ defines pheromone evaporation parameter, and the added pheromone on trail T(i, j) is governed by:

$$\Delta I_{ij}(t) = \mu f(t) \quad (16)$$

Where, parameter μ governs magnitude of concentration of pheromone and the visibility factor (heuristic value).

4. Result Validations

Having the algorithmic mathematical aspects in hand and the circuital-network parameters as tabled in Table 1, the following sections and subsections presents the simulated results in a MATLAB environment.

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	20
4	Corona Width (w)	5m
5	Angle theta (Θ)	π/6
6	Node Density (σ)	5
7	Initial energy ($\mathcal{E}_0$)	10J
8	Energy Consumption by transmitter circuitry(e_{elec})	50nJ/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

A 5-sectored network model is shown in Figures 5 (a) and 5 (b). All results presented below are subjected this model.

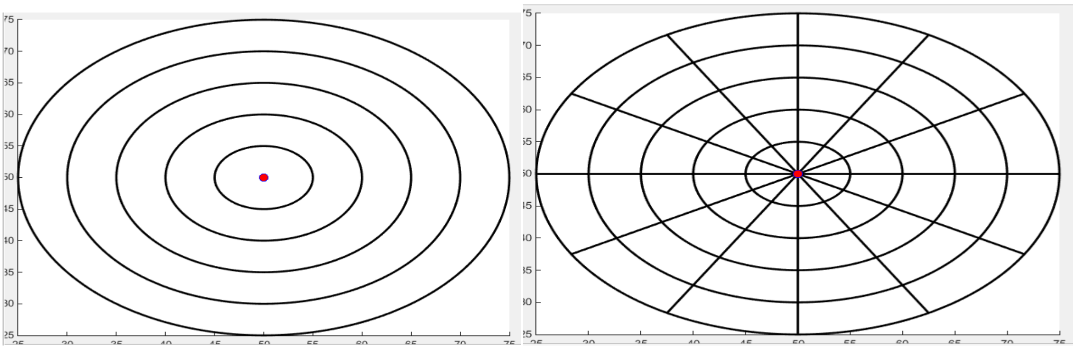
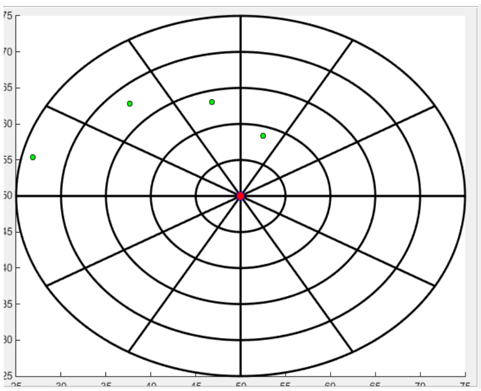


Fig. 5 (a): Sector model   Fig. 5 (b): Network model

Figure 5: Simulated five sectored models

4.2: Node deployment and Ant Movements

This proposed methodology uses programmed manual nodal deployment in which nodes are placed at the stroke of the mouse, instead of programmed random nodal deployment. Figure 6 (a) represents programmed manual node placement, wherein four nodes are placed manually. 6 (b) represents initial ant movement with farthest movement first, 6 (c) represents the last hop of last ant's movement and 6 (d) represents a typical final balanced energy optimum path for a typical energy level. This optimum path corresponds to minimum value of maximum average nodal energy consumption (ECPN) [12 & 13]. The favorable path (optimum path) represents average value of maximum ECPN. Minimum the value greater is the lifetime. Figure 6 (d) shows almost a balanced path.



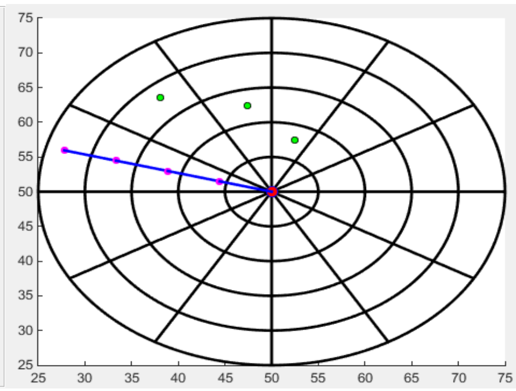


Figure 6 (a): Sample manual node deployment   Figure 6 (b): Initial ant movement (most outer sector first)

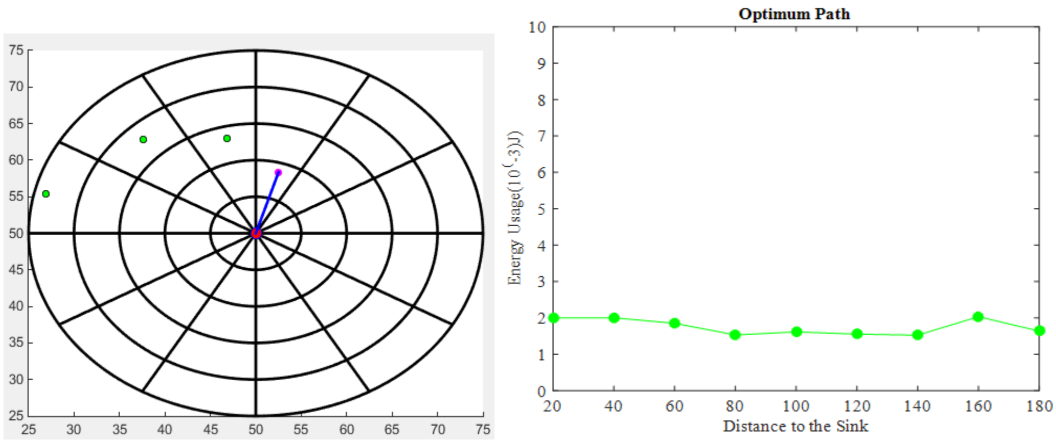


Figure 6 (c): Ants last hop final movement   Figure 6 (d): Optimum path

Figure6: Node deployment and Ant movements

4.3: Distance Estimations

Sample simulated values of best efficient-energy distance (BEED) and best balanced-energy distance (BBED) for every sector [12 & 13]is tabled in Table 2. These distances are for minimizing the total use of energy along the route of transmission and are simulated as per the modeling equations dealt with in section 3. If the same path is followed, then the overall energy usage will be seen reduced giving corresponding increase in network lifetime.

Table 2: Best efficient and balanced distances for 5-sectored model

Best energy-efficient distance (BEED)	Best balanced-energy distance (BBED)					
		1	2	3	4	5
2.7735	1	5.3709	6.9338	8.2041	9.3026	10.2844
	2	3.7796	6.6712	8.6444	10.2443	11.6260
	3	0.0000	4.6169	7.4259	9.4325	11.0815
	4	0.0+	0.0	5.386	8.0256	9.990
	5	23.4930	23.8988	24.2978	24.6904	25.0768

4.4 Data VolumeEstimations

Total data volume is estimated as per thesectored self-generated data volume and received data volume. Table 3 presents the simulated values of total data volume.

Table 3: Total Data Volume for 5-sectored model

	1	2	3	4	5
1	0	0	0	0	0
2	2.0944e+05	3.6652e+05	4.8287e+05	5.7450e+05	7.5398e+04
3	4.1888e+05	7.3304e+05	9.6575e+05	1.1490e+06	1.5080e+05
4	6.2832e+05	1.0996e+06	1.4486e+06	1.7235e+06	2.2619e+05
5	8.3776e+05	1.4661e+06	1.9315e+06	2.2980e+06	3.0159e+05
6	1.0472e+06	1.8326e+06	2.4144e+06	2.8725e+06	3.7699e+05
7	1.2566e+06	2.1991e+06	2.8972e+06	3.4470e+06	4.5239e+05
8	1.4661e+06	2.5656e+06	3.3801e+06	4.0215e+06	5.2779e+05
9	1.6755e+06	2.9322e+06	3.8630e+06	4.5960e+06	6.0319e+05
10	1.8850e+06	3.2987e+06	4.3459e+06	5.1705e+06	6.7858e+05
11	2.0944e+06	3.6652e+06	4.8287e+06	5.7450e+06	7.5398e+05
12	2.3038e+06	4.0317e+06	5.3116e+06	6.3195e+06	8.2938e+05
13	2.5133e+06	4.3982e+06	5.7945e+06	6.8941e+06	9.0478e+05

4.5: Average value of energy consumption per node (ECPN) of Sector and Network Lifetime.

ACO operation uses transition probability which is associated with pheromone intensity and heuristic value that are used in finding optimal path. The average value of energy consumption per node (ECPN) [12 & 13] for every sector is simulated. The smaller the value of ECPN, the more is the lifetime. Table4represents the simulated values of average ECPNat different energy levels concerning sink distances and Table 5 represents network lifetime concerning network radius. As seen from the table 5, the more the radius less is the lifetime.

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

Sl. No.	Distance to the Sink in meters	Energy Levels		
		K=6	K=8	K=10
1	20	1.9990	1.4789	2.3680
2	40	2.0016	1.5222	1.5558
3	60	1.8490	1.3071	2.2112

4	80	1.5294	1.8734	1.6519
5	100	1.6130	1.8560	1.4965
6	120	1.5519	2.1085	1.5964
7	140	1.5241	1.8817	1.7772
8	160	2.0319	1.9165	1.6892
9	180	1.6363	2.1014	2.0403

Table 5: Network Lifetime

Sl. No.	Network Radius in meters										
	100	110	120	130	140	150	160	170	180	190	200
1	9.2066	8.9768	8.2263	7.6553	6.8852	5.8835	5.2395	5.0390	4.8346	4.2409	3.9120

4.6: Transmission Level (K) Vs. Network Lifetime

The influence of the maximum level K of transmission on the lifetime for the proposed algorithm is depicted in Figure7. Higher the level, better is the efficiency and energy balance but, at certain level of K (k=8, 9 and 10), the lifetime becomes stable indicating higher energy efficiency for longer communication distance [12 & 13]. As seen from the graphs, as radius varies, the value of K also varies from K=8 to K=10 indicating rise in traffic near to the sink as area grows.

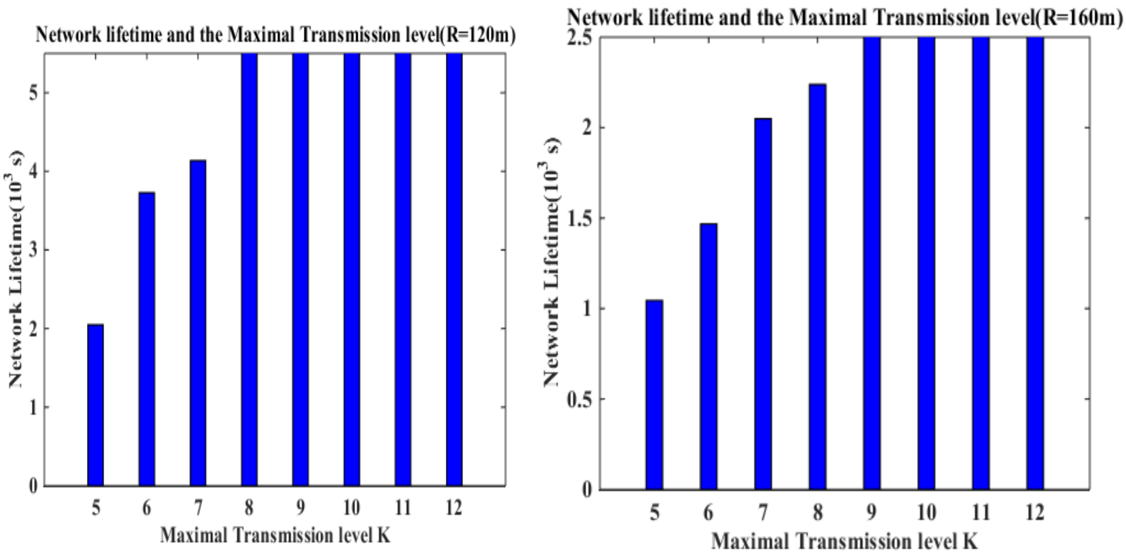


Figure 7(a):Energy level vs. network lifetime (R=120m) Figure 7(b): Energy level vs. network lifetime (R=160m)

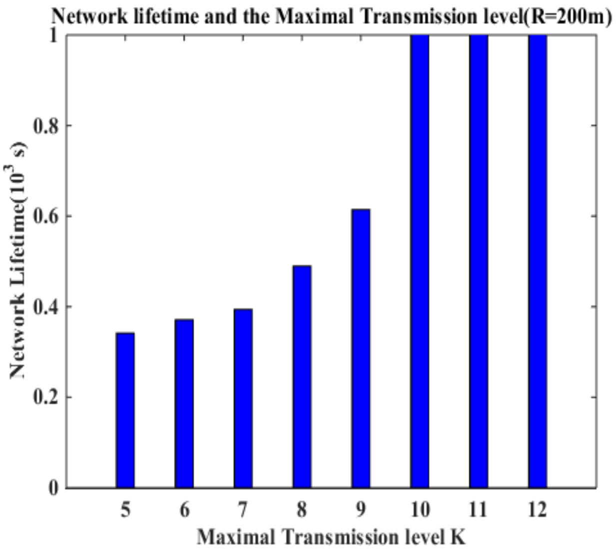


Figure 7(c): Energy level vs. network lifetime (R=200m)

Figure 7: Simulated Graphs showing relation between Transmission level and Network Lifetime for different radius: (a) R=120m (b) R=160m and (c) R=200m.

4.7: Network Lifetime for Various Radii's.

The simulated graph in figure 8 depicts lifetime for different transmission methodologies at different network radii. The comparison is for transmission strategies such as Single-Hop (SH) [5], Mutli-Hop (MH) [5], Hybrid (combination of SH and MH) [6], EAACA [9], EEABR [11]and the proposed ACO based most favorable distance (MFD) strategy [12 & 13]. The simulated graph shows that,as the network radius increases,lifetime decreases because of increase in traffic load. At a network radius value of 100 m, the proposed (MFD) network lifetime touches9.2 x 10^3 s and for others 1.5 x 10^3 s (SH), 2.8 x 10^3 s (MH), 3.2 x 10^3 s (Hybrid), 3.8 x 10^3 s (EAACA) and 6.8 x 10^3 s (EEABR). The proposed strategy performance far better than the rest because the proposed algorithm works on optimum distances both for energy efficiency and load balancing. The fallout of other transmission strategies isbecause of long-distanced communication(SH), less load balancing in MH, EAACA and EEABR.

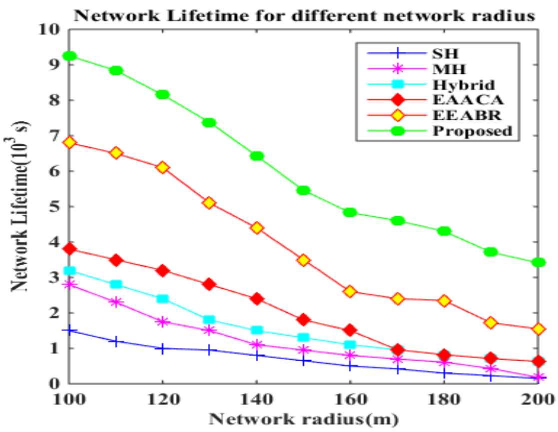


Figure8: Comparative plot for different transmission strategies

5. Conclusion

Wireless sensor networks (WSNs) have nodes that are vital elements of the Internet of Things (IoT) [19]. The nodes in such configurations run out of energy quickly because of this an optimum communicative abstraction is needed to have a prolonged network lifetime. The energy constraints are still existing even though harvesting technologies [20 & 21] such as solar energy are in force. Networks working lifetimefalls as node deployment grows. Amost favorable distance-based ACO algorithm is proposed wherein a best efficient-energy distance (BEED) and best balanced-energy distance (BBED) are implemented for high energyefficiency and load balancing. Based on the considered system model and maximum transmission level, an optimum path is established by running anACO algorithm.Ants use their pheromone intensity and its visibility factor to trace an optimum path. WSN's lifetime maximization is achieved with minimum value of maximum energy consumption per node (ECPN).The work can be extended by considering throughput with even and uneven distributed nodes and distributed nodal energy. The validity of this work will be used in real time to implement a medical application with due modifications and enhancement.

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