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Cluster-based routing protocol in wireless sensor network

Shireen Bashar Ghanem, Aws Zuheer Yonis
Department of Electronic Engineering, College of Electronics Engineering, Ninevah University, Mosul, Iraq

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ABSTRACT

Wireless sensor networks (WSNs) play a crucial role in various domains, including military, industrial, and environmental applications, due to their capability to monitor and transmit data efficiently. However, one of the major challenges in WSNs is energy consumption, as sensor nodes rely on limited power sources for data acquisition, processing, and communication. Efficient energy management is essential to prolong network lifespan and maintain performance. To address this issue, several energy-efficient routing techniques have been developed. Among these, the low-energy adaptive clustering hierarchy (LEACH) has gained significant attention for its ability to optimize power consumption through hierarchical clustering. This study investigates the performance of the LEACH protocol under different deployment configurations. We proposed and evaluate a circular sensing field as an alternative to the traditional square and rectangular field. Simulation results show that the circular field achieves better energy efficiency and network longevity across various packet sizes and base station (BS) locations. These findings highlight the importance of deployment geometry in enhancing WSN sustainability.

Corresponding Author:

Aws Zuheer Yonis
Department of Electronic Engineering, College of Electronics Engineering, Ninevah University
Mosul, Iraq
Email: aws.yonis@uoninevah.edu.iq

1. INTRODUCTION

Wireless sensor networks (WSNs) have gained popularity due to their use in various disciplines and real-time applications [1]. These networks consist of numerous small, separate sensing nodes placed in difficult-to-reach areas [2]. Wireless sensors are micro-electro-mechanical system devices (MEMS) with sensing, processing, communication, and power units [3], as shown in Figure 1. The application-specific sensing subsystem uses multiple sensors, while processors in the computing subsystem compute and analyze sensor data. Moreover, communication system technology allows sensor nodes to wirelessly link and share data, while the power subsystem powers the system [4]. These nodes detect environmental elements, record events, analyze data, and send it to a BS. Data can include temperature, water levels, air humidity, and other physical events [5]. Sensor node publishing sites are challenging to access, and for successful monitoring, they must remain in place. WSN research focuses on energy efficiency to extend battery life and network reliability. Proper energy distribution is a top priority to prevent sensor node depletion [6]-[10]. Routing protocol design is an active research field contributing to prolonging network life.

Cluster-based and hierarchical routing methods are popular for extending network lifespans and improving energy efficiency [11]. The cluster head (CH) collects data from member nodes, reducing BS data transfer. Clustering and data transmission continue until all nodes' batteries die [12], [13]. Most validated clustering approaches focus on CH selection, which mediates between sensor and sink nodes and is critical for WSN energy economy estimation [14]. Wireless power transfer (WPT) technologies can also address energy problems in WSNs [15], [16].

This work intends to improve cluster-based routing mechanisms, thereby increasing energy efficiency and extending network lifetime in WSNs. The following sums up the main goals and contributions of this research:

- Presenting a better CH selection method whereby, as in the traditional LEACH process, CHs are chosen every ten rounds instead of every round. This lowers energy consumption and helps to minimize the overhead connected with regular CH elections.
- Letting direct transmission for nodes close to the BS, so saving energy by removing the need for them to form a cluster.
- Using an adaptive communication system whereby nodes are driven by energy-aware conditions rather than limited to joining the closest CH or BS depending solely on distance.
- Suggesting a circular deployment area for WSN nodes and contrasting its performance with the square field layout. Under different BS positions and packet sizes, the simulation results show that the circular field generates improved energy distribution and a longer network lifetime.

The paper is organized as follows: section 2 discusses WSN routing protocols; section 3 discusses the related work; section 4 discusses model of the network and radio communication system; section 5 discusses simulation setup; section 6 discusses results; and section 7 discusses conclusion.

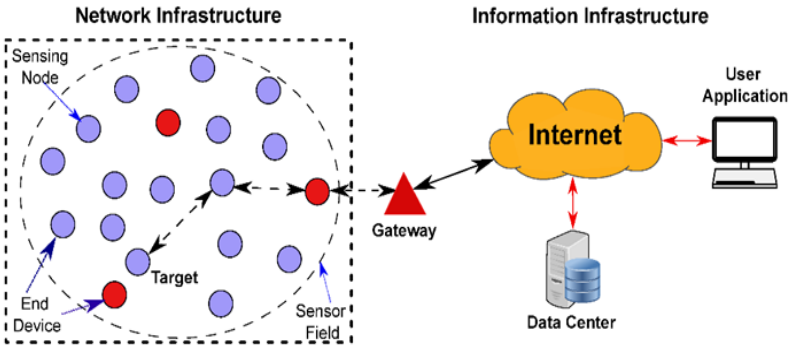


Figure 1. Architecture of sensing node [17]

2. WSN ROUTING PROTOCOLS

Routing protocols are reactive, proactive, or mixed. Reactive paths are computed only when needed, while proactive paths are pre-calculated and saved in a routing table for each node, making them undesirable in networks with hundreds of sensing nodes. Mixed therapies combine reactive and proactive methods. Location-based, hierarchical, and flat routing protocols are utilized in network flow design. Flat-routing increase data redundancy by assigning similar jobs to sensor nodes that give data independently [18]. Hierarchical protocols aim to maximize network efficiency, longevity, scalability, and sensor node range. CH selection and cluster routing achieve this [18]. Location-based protocols include sensor node distance and data transmission energy.

3. RELATED WORK

Researchers developed hierarchical routing technology as an approach to maximize wireless sensor network (WSN) operational lifetime. W.B. Heinzelman introduced LEACH in 2000 as the initial protocol to implement this methodology according to [19]. LEACH enables nodes in networks to construct regional groupings with each member having a central supervisory node. The cluster head (CH) takes charge of data collection from all cluster members while performing data processing before sending information to remote base station (BS) as Figure 2 demonstrates. The application of CH functionality increases a node's power consumption beyond non-cluster head nodes thus creating a potential problem that network cluster operations cease if a CH becomes inoperable [20], [21].

LEACH achieves equilibrium in energy expenses between nodes by rotating the cluster head position randomly thus preventing sensors from rapid battery depletion [23]. The cluster-head node creates a time-division multiple access (TDMA) schedule to enable node-to-node data transmission without generating cluster-wide signal collusions. A specific data communication schedule exists for clusters which takes into account entire member knowledge to ensure efficient cluster communication [24]. LEACH follows a systematic operation pattern where cluster formation occurs as the first stage of each cycle. Data collection occurs in the steady-state phase where the nodes send their collected data through the CH to the base station (BS) as illustrated in Figure 3 [24].

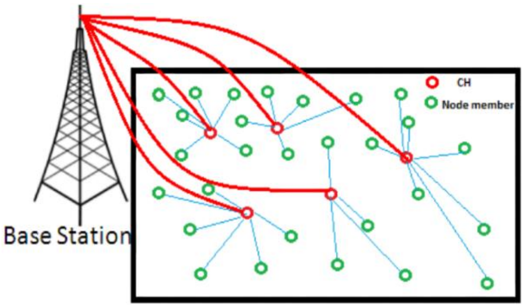


Figure 2. Cluster formation in LEACH [22]

Figure 3. Operation of LEACH [25]

Set-up phase: Every node makes its own evaluation for becoming the cluster head during this phase of the network. During this process node n creates a random value that ranges from 0 to 1 to determine the decision. The node selects to act as CH for the current round when its produced random number satisfies the condition specified as shown in (1) T(n).

$$T(n) = \frac{p}{1-p\times\left(r\times mod\frac{1}{p}\right)} \quad n \in G \tag{1}$$

G is composed of all nodes that did not function as CH in the last 1/P rounds, while P stands for CH proportion and n indicates the total node count, along with r representing the current round [26]. Using CDMA as its communication method, each CH node broadcasts ADV messages toward all neighboring nodes. The devices employed under regular nodes join the closest cluster head, while cluster head devices manage data transfer using time division multiple access (TDMA) through designated time slots. [27]. Steady-state phase: During the steady operating state, cluster nodes send their data to the designated Cluster Head through the assigned communication slot. The base station receives consolidated data from the CH through an efficient power-saving process. The stable phase extends to exceed the time duration of the cluster setup phase [28].

4. MODEL OF THE NETWORK AND RADIO COMMUNICATION SYSTEM

The energy model draws power for radio circuits and power amplifiers in both transmitter and receiver units, as Figure 4 displays. Based on the transmitter-receiver distance, the testing applied either free-space (d^2 power loss) or multipath fading (d^4 power loss) channel models. Specific control of the power amplifier helps minimize the transmission power wastage. Researchers prefer to employ the multipath (mp) model unless the distance is below a specific threshold (do) when they apply the free-space (fs) model. A radio will require transferring a k-bit message through d distance [15], (2), (3), and (4) provide the expression for the transmitted and received energy over k-bits.

$$\mathrm{E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d)} \tag{2}$$

$$E_{Tx}(\mathrm{k,d}) = \begin{cases} \mathrm{k} \times E_{elec} + \mathrm{k} \times \varepsilon_{fs} \times \mathrm{d}^2 & \mathrm{d} < d_o \\ \mathrm{k} \times E_{elec} + \mathrm{k} \times E_{Tx-amp} \times \mathrm{d}^4 & \mathrm{d} \geq d_o \end{cases} \tag{3}$$

$$\mathrm{E_{Rx} = k \times E_{elec}} \tag{4}$$

The energy throughput for a k-bit packet sent across d distance expresses the transmission requirements. ETX-elec(k) describes the amount of electrical circuit energy required for both transmission and reception processes relating to k bits. The computation of ETX-amp(k,d) includes amplification energy together with packet length and sender-receiver distance parameters. A data packet reception requires energy which is represented by ERX(k).

$$d_o = \sqrt{\varepsilon fs/E_{Tx-amp}} \tag{5}$$

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{6}$$

The amplifier energy, $\varepsilon fs\ d^2$ or $E_{TX\text{-}amp}\ d^4$, is dependent on the distance to the receiver and the permissible bit-error rate, whereas the electronics energy, E_{elec}, is determined by parameters including digital coding, modulation, filtering, and signal spreading.

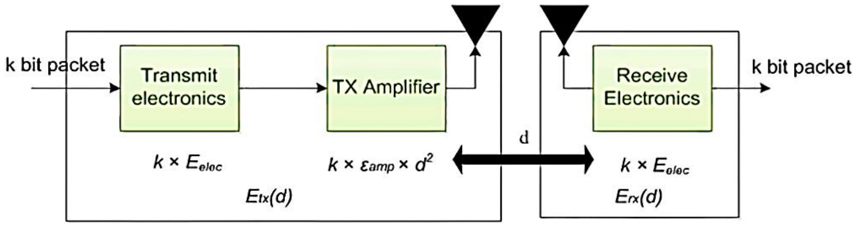


Figure 4. Radio energy dissipation model [24]

5. SIMULATION SETUP

A simulation was run using 80 homogeneous nodes, each with a starting energy level of 0.5 J. These nodes were arranged at random over a sensor field of 100 × 100 m^2. In another scenario, the same number of nodes was deployed inside a circular field with a radius of 50 m and a central at (50,50) to examine the effect of the field shape on energy consumption and network lifetime. The BS was positioned at two different locations: one near the center of the field at (30,30), and another far at (70,150) The sent packets included 2000,4000 bits, with 100 bits reserved for control packets. The parameters of the simulation model were modified as shown in Table 1.

Table 1. Simulation model's parameter

Parameters	Values	Parameters	Values
Field shape	Square (100×100 m^2) and circular (radius = 50 m, center at (50,50))	Amplification energy for short distances	10 PJ/bit/m^2
Number of sensor nodes	80	Receiver energy	50 nJ/bit
Location of the base station	(75,150), (30,30)	Amplification energy for long distances	0.0013PJ/bit/m^2
Packet size	2000,4000 bits	Data aggregation energy	0.0013PJ/bit/m^2
Initial energy for each node	0.5 J/node	Simulation rounds	5000
Transmitter energy	50 nJ/bit	Environment	MATLAB

6. RESULTS AND DISCUSSION

The research investigates different LEACH protocol deployments through simulation to study how WSNs respond to field designs and protocol control parameter selections in terms of energy management and performance results. Network lifetime with energy usage gets examined through analyzing field configurations and base station placement and packet size measurements. The stability and lifetime assessment of the network relies on three crucial performance indicators which include active node count and energy usage rate and network failure events. As depicted in Figure 5 the sensor nodes enqueuer their positions into square and round fields at different locations of the base station. The BS shows a green star indicator among normal nodes which connect to cluster head devices (CHs).

To analyze the effect of BS location, field shape, and packet size on network lifetime, two BS positions are considered: a near position at (30,30) and a distant position at (70,150). For each location, two packet sizes are tested—2000 bits and 4000 bits. Figures 6 and 7 present the number of alive nodes over simulation rounds for these configurations. Figures 6(a) and 7(a) represent the results with 2000-bit packets, and Figures 6(b) and 7(b) show the results with 4000-bit packets. Within each subplot, a direct comparison is made between square and circular fields, providing a clear view of how deployment geometry affects the longevity of the network under different conditions.

As shown in Figure 6, when the BS is located at (30,30), the circular field demonstrates a better performance in maintaining active nodes over time compared to the square field. In Figure 6(a), with a 2000 bits packet size, the first node dies (FND) occurs later in the circular field, indicating more efficient energy distribution. In Figure 6(b), although both fields show a reduction in lifetime due to the increased packet size, the circular topology still maintains an advantage, highlighting the benefits of compact node arrangement when the BS is centrally placed.

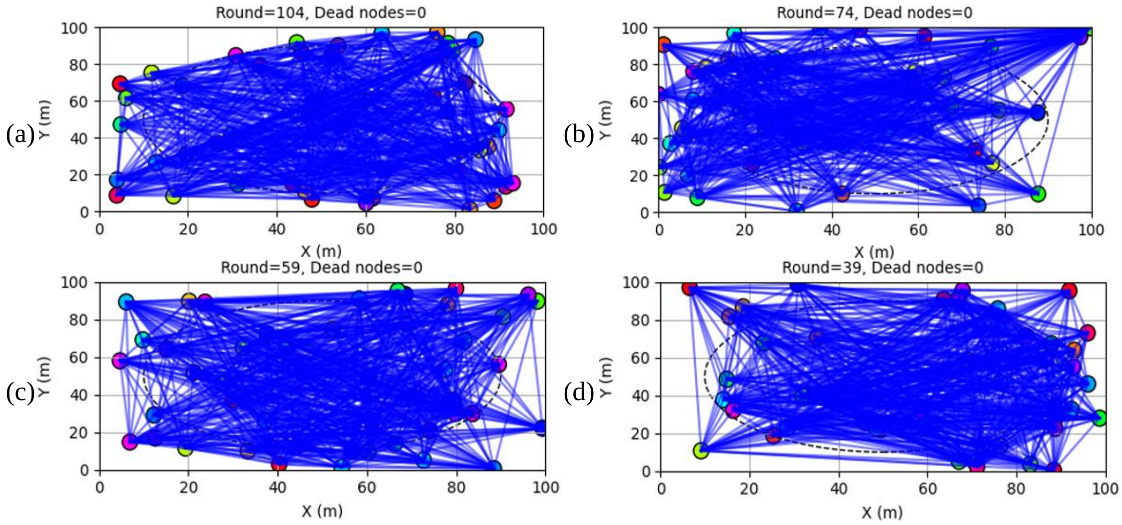


Figure 5. Network deployment with different BS positions: (a) square, BS at (30,30); (b) circle, BS at (30,30); (c) square, BS at (75,150); and (d) circle, BS at (75,150)

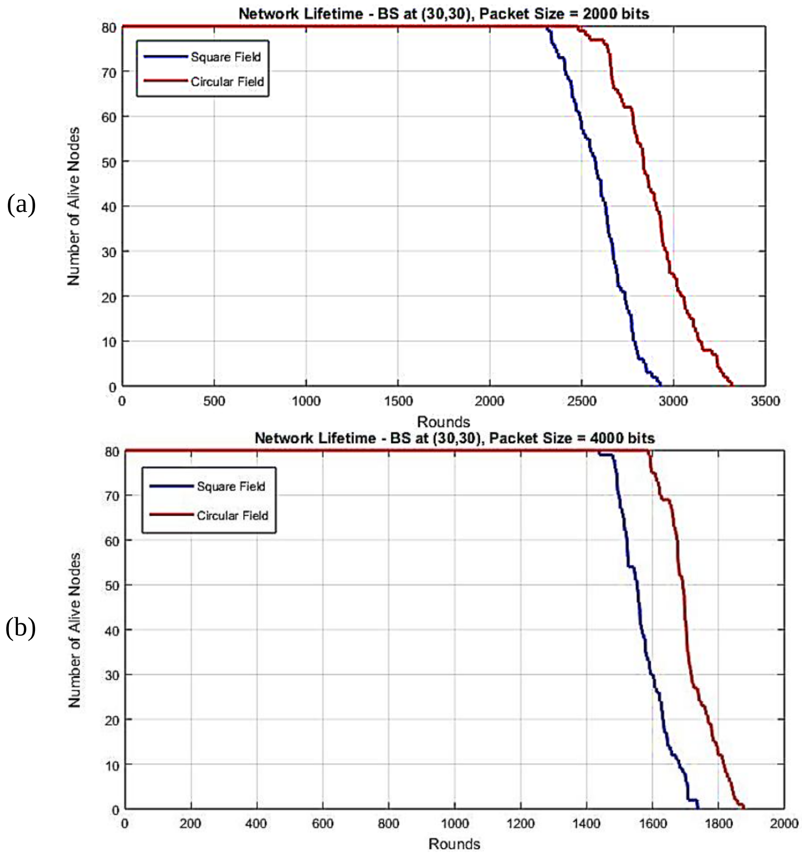


Figure 6. Network lifetime with BS at (30,30): (a) packet size = 2000 bits and (b) packet size = 4000 bits

Figure 7 shows the network lifetime results when the BS is placed at a farther location (70,150). In this scenario, the gap between square and circular fields becomes narrower. Figure 7(a) indicates that both fields experience earlier node deaths due to the increased average transmission distance. With 4000-bit packets (Figure 7(b)), the network lifetime is significantly reduced in both cases, but the circular field still slightly outperforms the square one in terms of stability and delay in FND and LND. These results suggest that the BS location plays a more dominant role when positioned far from the sensor field.

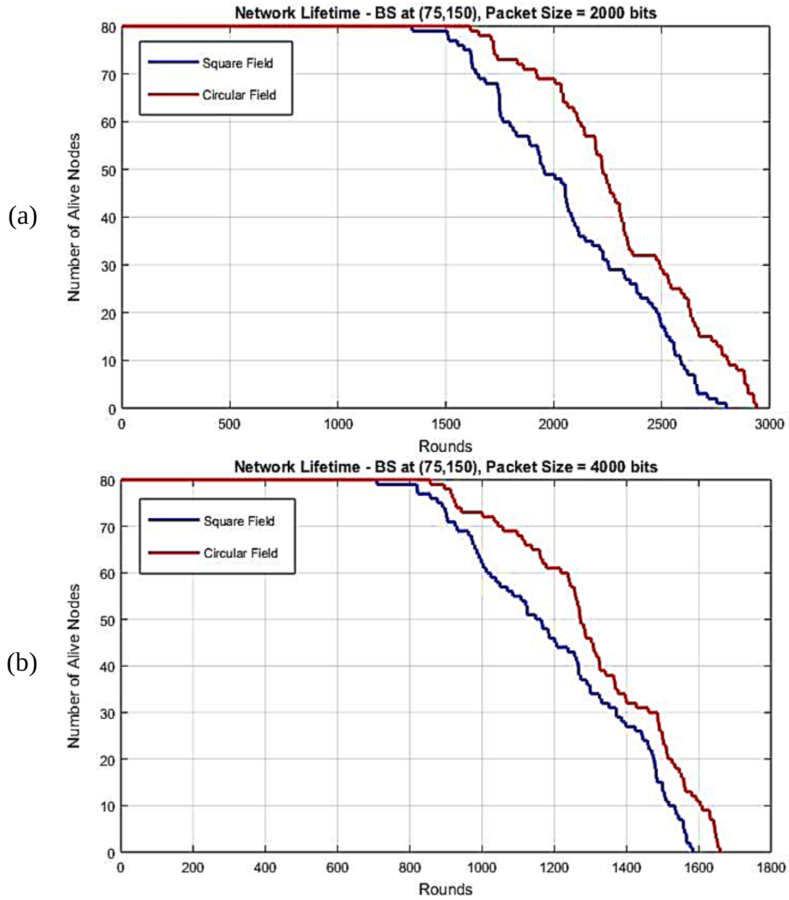


Figure 7. Network lifetime with BS at (75,150): (a) packet size = 2000 bits; (b) packet size = 4000 bits

To complement the graphical analysis of network lifetime, Table 2 summarizes the key node death statistics across all simulation scenarios. These metrics include the round at which the first node dies (FND), the round at which half of the nodes are dead (HND), and the last node dies (LND). The table covers all combinations of field shape (square and circular), BS location ((30,30) and (70,150)), and packet size (2000 bits and 4000 bits). This numerical summary provides a clearer view of the differences observed in the simulation figures and allows for direct comparison between deployment strategies.

The data in Table 2 indicates that circular field deployments consistently outperform square ones across all performance metrics. For instance, scenario S1 (circular field, BS at (30,30), 2000-bit packets) records the highest LND of 3315 rounds, while scenario S8 (square field, BS at (75,150), 4000-bit packets) records the lowest LND of 1585 rounds. This confirms that circular topologies better distribute energy consumption, likely due to more centralized communication paths. Moreover, placing the base station closer to the sensor nodes (e.g., at (30,30)) leads to significantly improved network lifetime. When the BS is relocated to (75,150), a drop is observed in all three metrics—FND, HND, and LND—regardless of the field shape. Additionally, increasing the packet size from 2000 to 4000 bits negatively impacts energy efficiency, as seen in scenarios S1 vs S3 and S2 vs S4. This is attributed to the higher energy demand for transmitting larger packets. Overall, the combination of a circular field, a centrally placed BS, and smaller packet sizes proves to be the most energy-efficient configuration, leading to extended network operation.

In addition to network lifetime, energy consumption plays a vital role in evaluating the performance and sustainability of WSNs. Figures 8 and 9 present the total energy consumption under two distinct BS locations: (30,30) and (75,150). Each figure includes two subplots for different packet sizes (2000 bits and 4000 bits), allowing for a comprehensive comparison between circular and square field deployments.

As shown in Figure 8(a), the circular deployment consumed less energy compared to the square configuration, particularly at lower packet sizes. This can be attributed to more uniform node distribution and shorter average transmission distances. In Figure 8(b), although the overall energy consumption increased due to larger packet size, the circular area still maintained better energy efficiency.

Figure 9 shows the BS outside the sensing field at distances of 75 m and 150 m. At 2000-bit packet size (Figure 9(a)), the circular field again outperforms the square field, achieving around 3000 rounds versus just 2700 rounds. However, when the packet size is increased to 4000 bits (Figure 9(b)), both topologies have drastically shorter lifetimes: the circular field lasts approximately 1700 cycles, while the square field lasts less than 1600 rounds. These findings demonstrate how field shape, BS location, and packet size all influence network efficiency and longevity, with circular fields providing greater resilience in both internal and external BS scenarios.

Table 2. Comparison of network performance metrics across different field shapes, BS locations, and packet sizes

Scenario	Field	BS	Packet size	FND	HND	LND
S1	Circle	(30,30)	2000 bits	2481	2904	3315
S2	Square	(30,30)	2000 bits	2314	2628	2925
S3	Circle	(30,30)	4000 bits	1588	1702	1876
S4	Square	(30,30)	4000 bits	1439	1567	1738
S5	Circle	(75,150)	2000 bits	1615	2310	2941
S6	Square	(75,150)	2000 bits	1345	2081	2800
S7	Circle	(75,150)	4000 bits	857	1326	1660
S8	Square	(75,150)	4000 bits	709	1266	1585

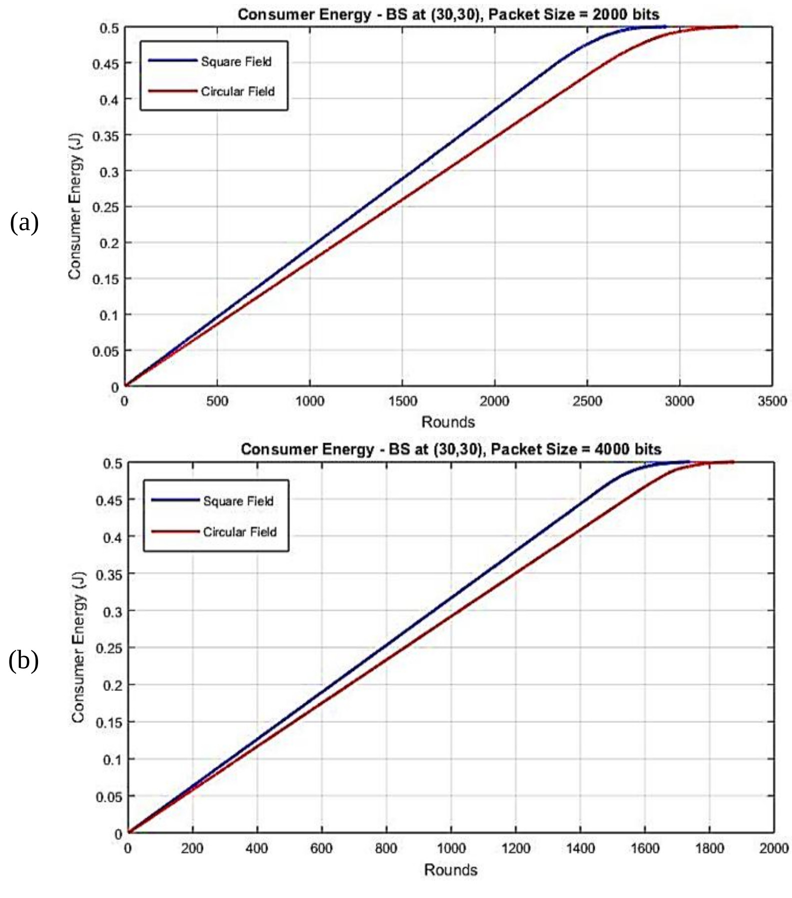
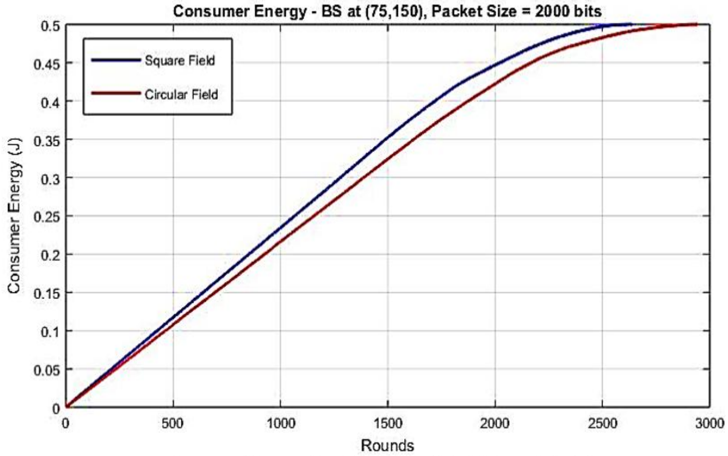


Figure 8. Consumer energy for BS location at (30,30): (a) 2000 bits packets; and (b) 4000 bits packets under circular and square field

(a)



(b)

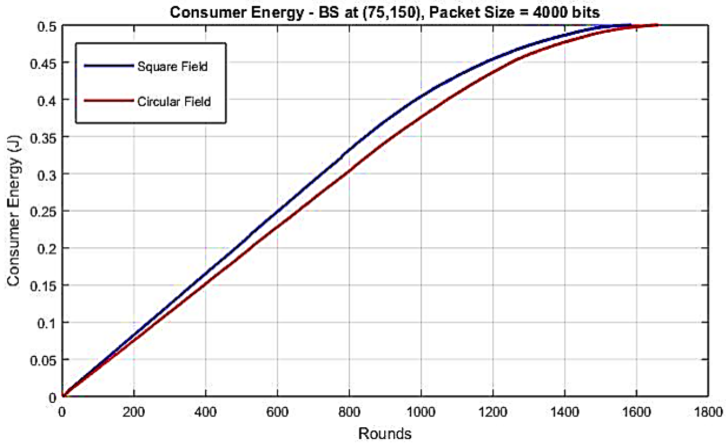


Figure 9. Consumer energy for BS location at (75,150): (a) 2000 bits packets; (b) 4000 bits packets under circular and square field

This paper looks at how stable networks are in WSNs by assessing how different field shapes, BS locations, packet sizes, and energy distribution affect network performance. We summarize the main achievements and contributions as follows:

- Effect of field shape: Under the same conditions, circular fields often provide better FND, HND, and LND values than square fields. This conclusion suggests that circular setups may use energy more evenly because they spread out the nodes better and have shorter average communication distances.
- Impact of BS locations: Placing the BS closer to the center of the field—that is, at coordinates (30, 30)—improves network performance and increases node lifespan. In 2000-bit situations (S1 and S2, for example), circular field nodes remain far longer than those in the square field. Relocating the BS to a distant location (75,150) does, however, clearly reduce lifespan measurements for both field types, with square fields most negatively impacted.
- Influence of packet sizes: Increasing the packet size from 2000 bits to 4000 bits lowers all lifespan measurements in every situation. We predict this result because larger packets consume more transmission energy, which speeds up node depletion. For a circular field with the BS at (30,30), for instance, the LND lowers from 3315 rounds (S1) to 1876 rounds (S3) because of the higher packet size.
- Optimal configuration: S1 (circular field, BS at 30,30, and 2000-bit packets) obtains the best-performing scenario with regard to node lifespan. On the other hand, S8 (square field, BS at 75,150, and 4000-bit packets) displays the lowest performance, therefore verifying that greater communication distances coupled with bigger data contents rapidly drain node energy.

7. CONCLUSION

In the study, the effects of deployment topologies, BS placements, and packet sizes on energy efficiency and network lifetime of wireless sensor networks (WSNs) with LEACH protocol are studied. The findings indicate that circular field deployments are better in terms of network lifetime compared to square topologies because of uniformity in energy consumption and shorter communication ranges that results in better energy efficiency. BS location has a great importance on the network performance, where centrally located BSs (e.g. at (30,30)) results in extension of lifetime as the communication distance will be less. In contrast, a remote BS (e.g. at (75,150)) reduces network lifetime, particularly in square field cases. Also, the fact that the packet size is increased to 4000 bits reduces the network lifetime since more energy is needed to transmit the packet. The best configuration that gives maximized network life is a circular field structure where the BS is placed at the center and uses smaller packets as the size. The paper highlights that one of the key factors to increase the sustainability of WSN is the use of energy-efficient deployment procedures, which include placing central BSs or circular topologies. Future works can be done on hybrid topologies, energy harvesting and optimization of routing protocols to enhance efficiency of WSN.

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AUTHOR CONTRIBUTIONS STATEMENT

This study used the Contributor Roles Taxonomy (CRediT) to accurately describe each author's contribution. The contributions of each author are summarized as follows:

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Shireen Bashar Ghanem	✓	✓		✓	✓			✓	✓		✓			
Aws Zuheer Yonis	✓				✓	✓	✓			✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [AZY], upon reasonable request. Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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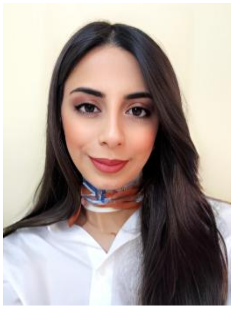
BIOGRAPHIES OF AUTHORS



Shireen Bashar Ghanem was born in 1996 in Ninevah, Iraq. She earned her B.Sc. in Electronic Engineering from the College of Electronics Engineering at Nineveh University, Mosul, Iraq. Currently, she is pursuing an M.Sc. in same department. Her research focuses on smart energy management systems for wireless sensor networks, optimizing energy efficiency and network sustainability. Her paper, titled Prolong the Lifetime of Wireless Sensor Network by LEACH Protocol, has been accepted for presentation at the International Conference on Artificial Intelligence, Metaverse, and Cybersecurity (ICAMAC 2024). She can be contacted at email: shereen.ghanem2014@stu.uoninevah.edu.iq.

Aws Zuheer Yonis graduated from Department of Computer Engineering in 2003 and completed his Master's and Ph.D. degree in Electrical and Electronics-Telecommunication Engineering at University Tun Hussein Onn Malaysia (UTHM) in 2011, 2013 respectively. Since 2006 he became an engineer at University of Mosul-Iraq. While he gets in 2020 an Assistant Professor degree in the Department of Electronic Engineering/College of Electronics Engineering at Ninevah University, Mosul, Iraq. He has published many research papers in international journals, books, and conferences. He can be contacted at email: aws.yonis@uoninevah.edu.iq.