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Mathematical Model Used to Compute Packet Energy Consumption-Based Control Topology for WSN

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Abstract

Several recent scientific papers have been proposed on power consumption in Wireless Sensor Networks (WSN). Still, the work focused on control topologies of WSN in the field of increasing and prolonging the whole network is limited. This results from their function as routers that send data from edge nodes to the sink. The nodes around the sink node quickly die while delivering much data through intermediate nodes from one node to the sink node. The network lifetime was reduced because the sensor nodes adjacent to the sink consume twice as much power as the others. This problem is not recognized and addressed in more visual detail by the authors. The nodes closest to the sink node will die first. Therefore, this paper proposed a mathematical model to represent packet energy consumption with control topology for WSN. Due to the simulation, more than 90% of sensors are still operational and optimally arranged. The overall battery power remaining in the sensors was greater than 70%.

Keywords: Data frame, Energy efficiency, Network lifetime, Network topology, Power consumption

1. Introduction

In WSN, energy efficiency is one of the main objectives of many authors. Where sensors have limited power. The routing protocols are the set of defined rules used to improve the performance of wireless networks [1]. Hence, some nodes may use the same route, leading to the exhaustion of intermediate nodes of this route. Each node's tasks require it to function independently as a host. In addition, some environments might be sensor nodes distributed in very hazardous areas. Hence, the nodes of WSN power are supplied through batteries with finite energy [2]. Consequently, it is important to increase the prolonged lifetime of WSN by minimizing energy requirements across all levels of the network. [3]. Control topologies are very important in growing prolonged networks in the WSN [4]. In addition, the IEEE 802.15.4 standard is intended to provision a long battery lifetime [5]. Whereas the Media Access Control (MAC) and PHY layers of Low-Rate Wireless Personal Area Networks (LR-WPANs), which are a low-cost, low-data-rate wireless access technology for devices that are operated or work on batteries, serve as the foundation for other higher-layer standards like ZigBee, 6LoWPAN, and MiWi [6]. However, some measures must be taken to make the standard applications for sensor network systems operate longer. Routing is a crucial component of every network and is crucial for reducing the power consumption of wireless sensor networks [7], [8]. Finding the optimum route increases the lifespan of WSN. To obtain energy savings over the entire network [9] that depend on allocating energy usage in the whole network evenly will be sufficient. When a high volume of data is sent by using intermediary nodes to connect one node to another, this causes a rapid dyeing node for individuals near the sink node [10]. Consequently, the whole network could crash. The sensor node closest to the sink drew more power than the others and failed more quickly, which reduced the network lifetime.

In 2018, Yang et al. [11] presented a novel carrier sense multiple access collision avoidance and time division multiple access hybrid scheme protocol medium access control on the MAC layer, improved performance while reducing energy consumption for mobile WSNs with 3-D position prediction algorithms. Shojafar et al. [12] presented and tested an adaptive energy approach for Networked Fog Centers (NetFCs) that could offer quality-of-service guarantees for traffic provided to vehicle clients, immediate rate jitters, and overall processing delays. In 2021, Asuti and Basarkod [13] showed that their suggested simulation results exceed DSME-GTS techniques regarding performance parameters, including packet delivery ratio, end-to-end latency, packet loss ratio, throughput, delay, bandwidth usage, and power consumption. In 2023, Diakhate et al. [14] evaluated the firefly approach to improvement, which picks the best cluster head from a set of nodes. They discovered that the proposed approach is better than conventional low-power adaptive clustering.

2. Mathematical Model to Calculate Packet Energy Consumption

The mathematical model considers several real-world measurements of the CC2420 radio's power throughout various operations. The network in this concept was based on unicast traffic and unicast mode. When receiving or sending information, the sensor uses energy [15]. This modeling reduces device and channel acquisition overhead by fixing related components. However, this simulation does not consider energy consumption, ineffective channel acquisition, and lost duo because wireless communication and a collision bit error have been lost.

In PAN, known as a LR-WPAN using CSM/CA, the IEEE 802.15.4 standard specifies the protocol and device interconnection [5]. This paper uses a new CSMA/CA structure that contains footer and header data frames with transfer reliability during packet transmission to investigate the channel acquisition overhead. One can determine the power usage of packet transmission by modifying the component and payload information to add the liner equation's rising components. A mathematical model will forecast the network's higher and lower authorization routing. This action must be completed as a crucial precondition to build a methodology. Other characteristics, including parameter transmission, must be considered while optimizing for low energy use. The energy a sensor node uses to send or receive a packet is represented in [16] using a linear equation (1).

$$\boldsymbol{Energy} = m \times size + b \tag{1}$$

where m stands for the added expense. While b stands for fixed expenses. The payload (data packet) is represented by size as several bytes. Consequently, the power needed to send a packet is [17].

$$Energy(\,send) = m(send) \times size + b(send) \tag{2}$$

Receiving the packet is

$$Energy(\,rec.) = m(\mathrm{rec.\,e}) \times size + b(\mathrm{rec.}) \tag{3}$$

The LR-WPAN defines four frame structures:

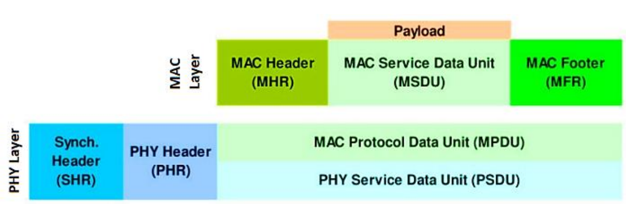


Figure 1. Shows MAC frame and physical layer

As shown in Fig 1. MAC frames come in 4 different flavors. A data frame is a tool for transferring data between nodes [18]. A coordinator node only employs a beacon frame, which will be disregarded. An acknowledgment frame confirms that a node has successfully received a frame (important). All MAC control transfers are handled via a MAC command frame. So, for management and control functions between nodes, beacon and MAC command frames are used [19]. The amount of power consumption for each frame is as follows:

2.1. Data Frame

According to Fig. 2 data frame layout, the transmitted data packet is made up of (11 + (0 to 20) + n) bytes [20], where n stands for payload data [21]. Where, in actuality, addressing takes up 6 bytes. In this case, the sensor is given two bytes of addresses, the source PAN identification is given two but left unoccupied, and the end PAN identifier is given two. As a result, the data packet's length is 11+6 + n bytes= 17 bytes + n bytes.

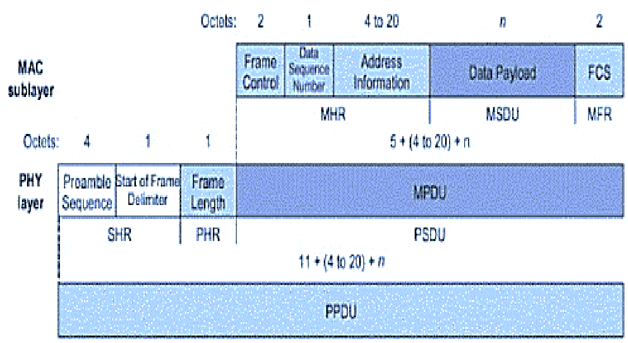


Figure 2. The data frame includes the number of bits for MPDU and PADU

2.2. Acknowledgment Frame

Based on the acknowledgment frame, the acknowledgment frame has a size of (11 bytes) [22]. However, it is important to transfer information between two nodes. Both transmitter nodes and receiver nodes exist. The sender node sends a data frame of 17 + n bytes and receives an acknowledgment frame of 11 bytes. The receiver node must also provide 11 bytes of acknowledgment information and receive a data frame of 17 + n bytes [23]. Synchronization services will be offered in IEEE 802.15.4, which disregards beacons sent by the coordinators [5].

To determine the CC2420's (a single-chip 2.4 GHz IEEE 802.15.4 compliant ZigBee) power consumption. If not used in PAN or MAC sub-layer, the syn of IEEE 802.15.4 should be transmitted using CSMA/CA by doing the following:

1. Set up a random back-off period or local back-off variables.
2. Then, the channel has been cleared; check to ensure it is clear.
3. The data transmission that follows.
4. The acknowledgment frame comes last.

The first internal step is to measure the route's maximum and minimum energy usage levels by the IEEE802.15.4 structure, a precise channel evaluation before delivering the acknowledgment [24]. Clear Channel Assessment (CCA) is a 46-byte packet that determines the power needed for transmitting. The header and footer are 18 bytes long, and the data payload is 28 bytes long. As a result, sending two bytes uses 0.24 mJ of energy, while sending 12 bytes and 20 bytes uses 1.44 mJ and 2.4 MJ of energy, respectively. Listening and Receiving: A 46-byte packet had to be received to measure the receiving power consumption necessary for listening and receiving operation. Before receiving data, there is a tiny periodic receive check lasting 10 ms that is being listened for, and it needs 0.58 MJ. However, according to the calculations in equation (3), it is rewritten into two questions, (4) and (5), as follows.

$$Energy\ (\,send) = (0.12) \times n + (3.54)\ \ mJ \tag{4}$$

$$Energy\ (\,rec.) = (0.12) \times n + (4.03)\ \ mJ \tag{5}$$

3. Network Lifetime

lifetime is the period from the network's initialization till at least one node dies. Also, it is referred to as "time to network partition ."The mathematical work of a network is known as topology [25], [26]. N are the nodes, E are the links, and (i, j) is a link from Node i to Node j in the topological graph G (N, E). Let f be the means of transmission for the data. The following is the definition of the variable X_{ij}^{f}:

$$X_{ij}^{f} = \begin{cases} 1, if\ link\ (i,j) is\ used\ for\ flow\ f \\ 0, if\ link\ (i,j) is\ not\ used\ for\ flow\ f \end{cases} \tag{6}$$

According to the equation above (6), if the data flows from node I to node j through the link, the variable vector $\mathrm{X}_{\mathrm{ij}}^{\mathrm{f}}$ is one if the vector is not transmitting, while zero is in all other cases.

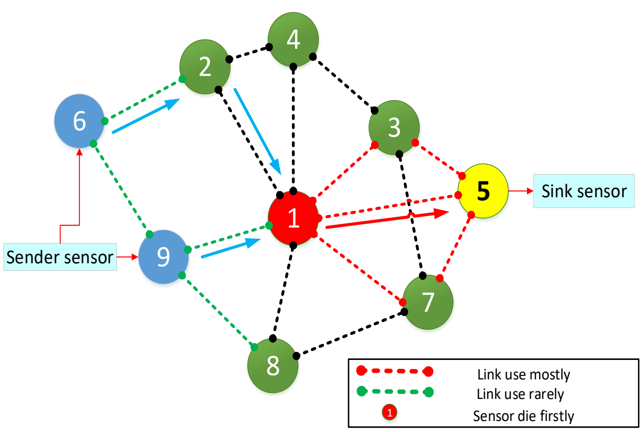


Figure 3. Part of the sensor network field

Indeed, to determine the total power available for one route. Equation (10) shows the expression of current power available in the nodes for a particular route from the source node to the target node [27], [28]. Where P_r denotes the amount of power consumption across a single route, h is the number of hops,

$$P_r = \{\textstyle\sum_{ij}^{h} \mathrm{X}_{\mathrm{ij}}^{\mathrm{f}}\ (NodePower_i)\} \tag{7}$$

Assume that Pr stands for the total amount of power required to transport an amount of data from one node to another node. The receiver and transmitter circuits $(E_{TX,}\ E_{RX})$ determine the power usage. For example, Fig. 3 shows Sensor 9 transmits only, Sensor 1 Receive and Transmit. Where the energy required to deliver *k* bits over *d* meters is [25]:

$$E_{Tx}(k,d) = E_{Tx\rightarrow elec}(k) +\ E_{Tx\rightarrow amp}(k,d) \tag{8}$$

There is a threshold distance that can consume more power. Therefore d_0 which can be calculated as equation (9) [26]:

$$do\ = \sqrt{\frac{\epsilon fs}{\epsilon mp}} \tag{9}$$

$$E_{Tx}(k,d) = \begin{cases} kE_{elec} + k\epsilon_{fs}d^2 & if\ d < d_0; \\ kE_{elec} + k\epsilon_{mp}d^4 & if\ d \geq d_0; \end{cases} \tag{10}$$

Where for the k-bit message, the radio will use energy throughout the receiving process [26]:

$$E_{Rx}(k) = kE_{elec} \tag{11}$$

4. Modeling Experimental

This section explains the experimental implementation and how to determine the best path by calculating the power usage for each one [29]. In this experiment, they utilized 100 sensors distributed randomly between nodes with an area (*100 m* × *100 m*) as shown in Fig. 4. Usually, in any experimental, they use different numbers of nodes as well as area, but as a paper written mostly use 100 nodes with area 100m*100m. The experimental simulation used 50, 100, 150, and 200 in different areas. Tnode is situated in the midpoint of the region and has unlimited power, as shown in Fig. 4, which is highlighted in green.

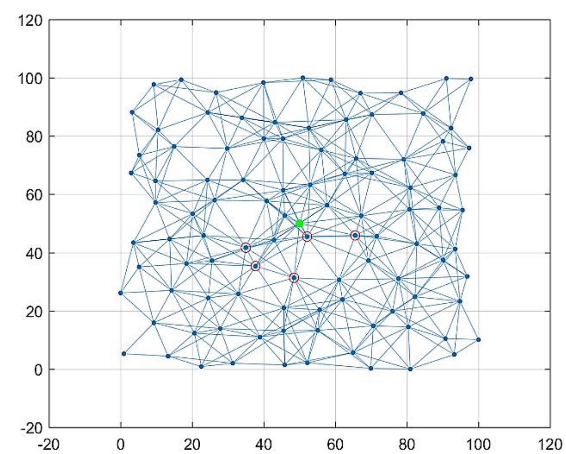


Figure 4. 100 sensors in a network with a sink node in the field's center

The sensor nodes use rechargeable type AA nickel metal hydride batteries. A nominal voltage exists in every battery. The battery's (C) charge capacity achieves its finish over time. For instance, assume a battery has a charge capacity = 1200 mAh for 1 hour. To calculate the required number of Joules as follows: E (J) = I × 3600 (sec) × V = 1200 (mA) × 3600 (sec) × 1.2 (v) = 5184 (J). Assume that the radio model uses 50 nJ of energy (E_{elec}) per bit to power the transmitter and receiver circuits. The data bits must be transmitted over a distance (d).

The model parameters are illustrated in Table 1 as standard simulations, and the authors must use these parameters because they are power consumption by transmission devices.

Table 1. Configuration parameter.

Name	symbol	Values
Energy per bit	E_{elec}	*50nJ/bit*
Entail Energy	E_o	*0.5J,0.1J*
No. of bits	*k*	*4000,140*
No. of nodes	*n*	*100*
Energy per bit of Amplifier if $d_{max} <= d_0$	E_{A1}	*10pJ/bit/m*
Energy per bit of Amplifier if $d_{max} >= d_0$	E_{A2}	*0.0013pJ/bit/m*
Zone	*x, y*	*100 m × 100 m*

According to the simulation results, the first Node ID is 34 dies after 325 data transmissions from random sensors. Then, as illustrated in Fig. 5, Nodes 35, 36, 44, and 46 die respectively.

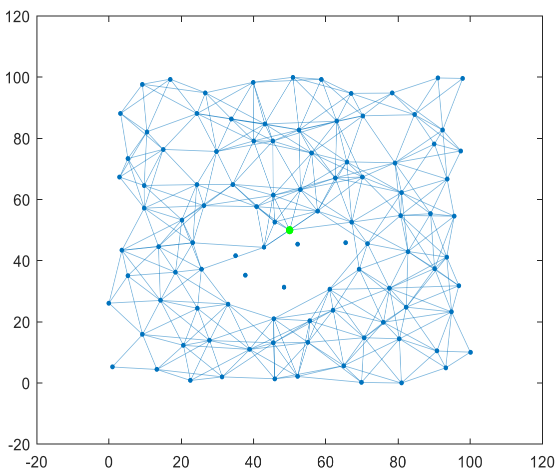
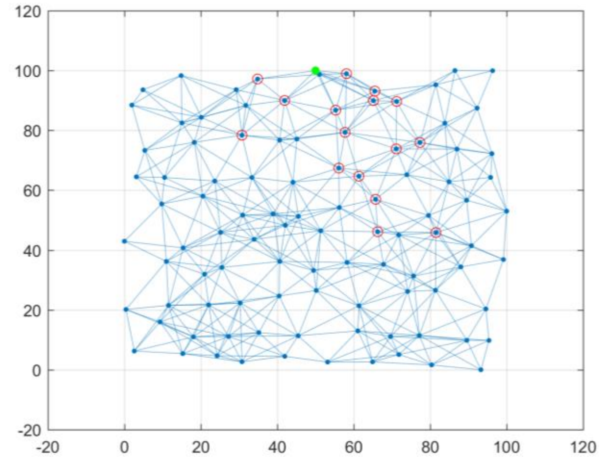
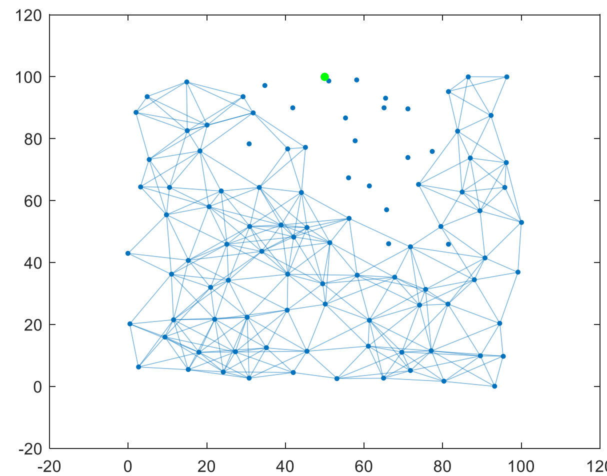


Figure 5. network topology with dying nodes after 325 transmuting.

After simulating with the same experimental method except for the sink node moving to the upper, as shown in Fig. 6, the first 16 nodes died after 325 sending data from random sensors. Also, a big gap between the sensors and the sink node leads to isolating all the remaining sensors. This leads us to conclude that the network design and control topology are very important. The network lifetime for the second experiment dies early. But still, the network lifetime for the first experiment is life after 325 of data transmuting.



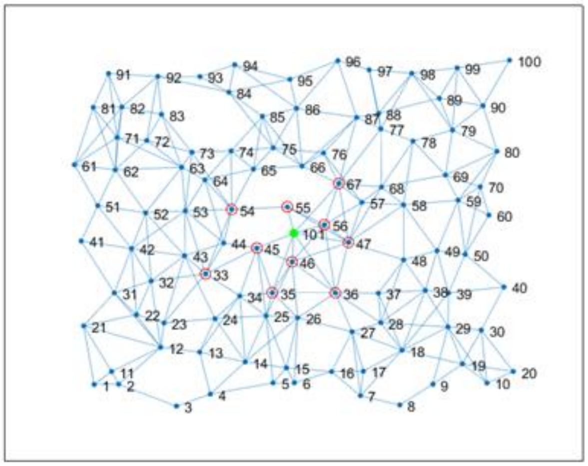
(a) Network structure including 100 sensors



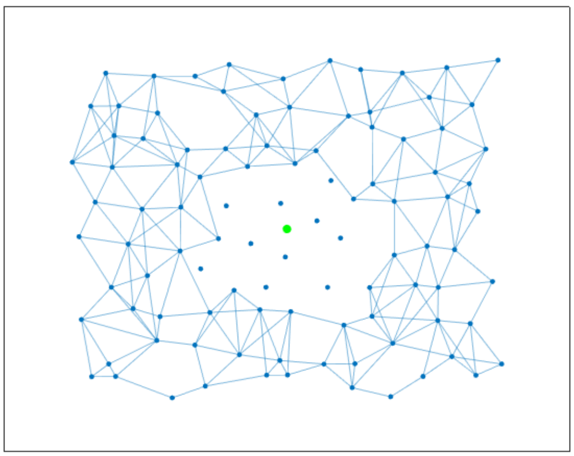
(b) network structure with dead nodes

Figure 6. Topology of the network with the sink node at the top.

In this work, another finding is illustrated in Fig.7. The nodes around the sink node experienced a large hole. Hence, the routing protocol does not evenly use all the network's nodes' power. Even when applying energy-aware protocols. Most nodes die for that reason close to the sink node since they are usually used as intermediate nodes while delivering data rather than edge nodes. Consume more energy as a result, then die first. Where the sensor IDs died are (33,35,36,45,46,47,54,55,56, and 67).



(a) network alive



(b) network die

Figure 7. Topology of the network with the sink node at the field's center.

Many experiments have been done with the same parameters in Table 1. For most of them, the network died, with less than five sensors dying. This depends on the sensors distributed and the control topology used. But even with the best circumstances and distribution, the network dies After very few sensors die (more than 90% of sensors are still live). The total power remaining in the sensors is more than 70%, which still exists (total battery power remains). The sensors lose connections with the sink node because of the gap, as shown in Fig. 7. Fig. 8 shows that the sensor's battery remains. Table 2 illustrates the details of battery charging for the sensors field.

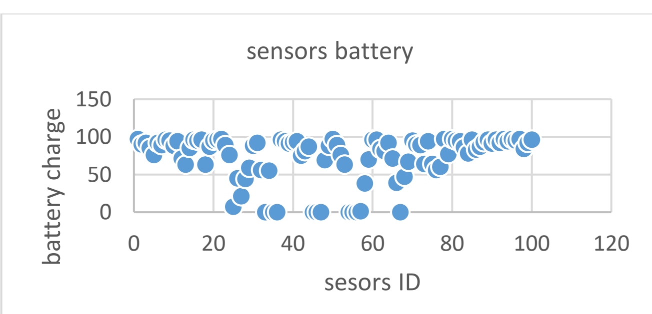


Figure 8. The sensor Battery remains for the sensor field.

Table 2: Details of battery charging for sensors field.

charge percentage	node ID	charge percentage	node ID	charge percentage	node ID	charge percentage	node ID	charge percentage	node ID
97	1	96	21	94	41	96	61	95	81
90	2	97	22	75	42	84	62	94	82
92	3	89	23	81	43	81	63	86	83
85	4	76	24	87	44	92	64	78	84
76	5	7	25	0	45	71	65	96	85
92	6	45	26	0	46	39	66	83	86
89	7	21	27	0	47	0	67	87	87
96	8	44	28	69	48	47	68	93	88
95	9	59	29	88	49	67	69	96	89
88	10	88	30	97	50	95	70	91	90
94	11	92	31	89	51	90	71	96	91
71	12	56	32	76	52	89	72	92	92
63	13	0	33	63	53	64	73	97	93
85	14	55	34	0	54	94	74	94	94
96	15	0	35	0	55	64	75	97	95
95	16	0	36	0	56	56	76	95	96
96	17	96	37	1	57	60	77	97	97
63	18	94	38	38	58	97	78	84	98
87	19	91	39	70	59	77	79	92	99
95	20	93	40	96	60	97	80	96	100

Some authors continue their experiment, although the network dies early due to the gap generated around the sink node [30]. As shown in Fig. 9 below, The nodes around the sink node quickly die while delivering a lot of data through intermediate nodes from one node to the sink node.

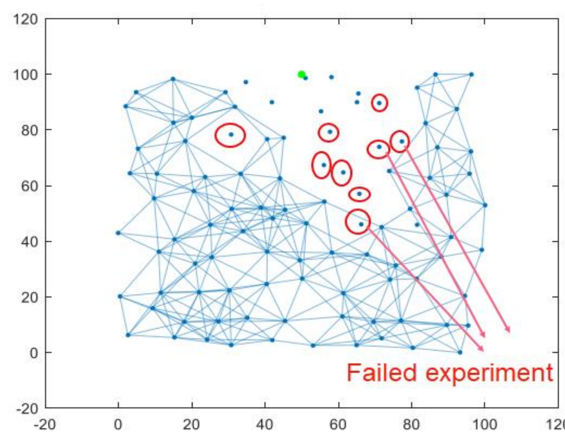


Figure 9. Network topology with dying nodes [30]

The authors do not recognize and address this problem in more visual detail. It has been proven that the network dies when the nodes closest to the sink nodes die, resulting in a large gap with the sink node. However, the authors continue to provide data and finish the experiment since the sink node cannot receive data. All the calculations in Fig. 9 are false and incorrect because the sink node cannot receive data after 5-7 die nodes.

As a result, the work's conclusion advises authors to use control topology in conjunction with any additional parameter to increase network lifetime in WSNs. If both parameters are dependent on each other, this lifetime can be effectively increased by distributing power across the entire WSN network.

5. Discussion

The main objective of this paper is to introduce two contributions. Firstly, a mathematical model of wireless sensor networks was represented. Secondly, the mathematical model was applied to an area (100 * 100) m2, including 100 sensors. Which is lead us to:

a) The nodes around the sink node quickly die while delivering much data through intermediate nodes from one node to the sink node. The network lifetime was shortened because the sensor nodes next to the sink consumed more power than the others.

b) In experiments 1 and 2, as shown in Figs. (5 and 6), the role of control topology, as well as node position in the network field, is very important. The network lifetime for the second experiment dies early. But still, the network lifetime for the first experiment is life after 325 of data transmuting.

c) After the network sensor field dies, a consequence gap between sensors and sink nodes accrues. More than 70% of the power remains in the sensors (total battery power remains). Also, more than 90% of sensors are still alive.

d) As a result, the work's conclusion advises authors to use control topology in conjunction with any additional parameter to increase network lifetime in WSNs. If both parameters are dependent on each other, this lifetime can be effectively increased by distributing power across the entire WSN network.

6. Conclusions

This work recommends the authors work on "control topology" and any other parameters to increase and prolong the network's lifetime. This work concludes the effect of “control topology” by using distributed power over the whole WSN network, leading to an increased prolonged network lifetime. It consumes energy obtained at each sensor's receive, send, and process. A mathematical model has been proposed to calculate power consumption in the WSN field. This work illustrates how intermediate nodes lead to fast dyeing nodes near the sink node. Also, those experiments showed us that the role of network design and control topology is very important. Because the network lifetime for the first experiment is still life after 325 data transmuting, it has been shown how the network sensors field dies due to the gap between sensors and the sink node. More than 90% of sensors are still alive, and the power remains in the sensors more than 70% (total battery power remains).

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Conflict of interests

Regarding publishing this paper, the authors state that they have no conflicts of interest.

Abbreviations

b	Fixed expenses
E_A	Energy per bit of Amplifier if
E_{elec}	Energy per bit
E_o	Entail Energy
k	No. of bits
MAC	Media Access Control
m	Added expense
n	No. of nodes
WSN	Wireless Sensor Networks
PAN	Personal Area Network

Author Contribution Statement

Mohammed Joudah Zaiter proposed the problem statement.

Tariq M. Salman developed the method of energy consumption computation using WSN topologies.

Abdalrazak Tareq Rahem verified the analytical methods investigated [control topologies of WSN] and supervised the findings of this work.

All authors discussed the results and contributed to the final manuscript.

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