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An Adaptive Activity Cycling Technique for Energy Management in Wireless Sensor Networks (WSNs)

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ABSTRACT: Wireless Sensor Networks (WSNs) consist of large number of small nodes that sense the surround environment and transmit the data to the central collection points. Since these nodes rely on batteries as power source, the effective power management considered as a vital to ensuring that the network continues to operate over long periods. In this research, we offer innovative adaptive activity cycling technique aims to enhance power management in “Wireless Sensor Networks”. The suggested technique rely on duty cycling concept, where the node is turned on for a certain period and turned off for another period to save energy. Our approach is characterized by dynamically adjusting the on and off periods based on changing network conditions. The adaptive cycling setup according network traffic, so that, in the low traffic cases, the off periods is increased to save power, while these periods decreases in the high traffic cases to ensure transmit data efficiently. In addition, the technique, regard remaining node battery level, which ensure node continue for longer possible period by modifying adapting cycles based on remaining battery level. Simulation tools NS3 and MATLAB are used to evaluate the performance of innovative technique. The results showed, the technique achieve significant enhancements in term energy consumption efficiency comparing with traditional techniques. Furthermore, the technology was able to maintain the quality of service in terms of response time reduction and increase packet delivery ratio. In conclusion, this research demonstrates that using adaptive activity cycling technique can contribute significantly in terms of prolong network lifetime and enhance “energy efficiency in Wireless Sensor Networks” without sacrificing the quality of service. This technology is promising and can be used in a variety of applications like procession agriculture, environmental monitoring, health care, which support the effectiveness and sustainability of wireless sensor networks in different environments.

Keywords: WSNs, Energy Management, Activity Cycling.

1. INTRODUCTION

The “Wireless Sensor Networks (WSNs)” considered as a vital technology in several fields like environmental monitoring, precision agriculture and healthcare. These networks highlighted by its ability to collect data form surrounding environments and then send it enteral processing station to make decisions based on collected data [1]. However, the main challenge that face these networks is the efficient energy management, that is because most of the sensor nodes are operate by batteries have limited capacity [2]. In the recent years, the energy efficient enhancement algorithms for Wireless Sensor Networks are suggested. These solutions range from energy-efficient routing protocols to advanced machine learning techniques [3], [4]. The activity cycling considered one of common methods to achieve this goal, where the sensor nodes are activated only when their needs, which reduces the energy consumption significantly [5]. Despite great progress in this field, there is still a need for more effective solutions to face the increasing challenges, which force it the recent applications. These applications required higher accuracy, higher confidently and lower response time. Which makes vital to develop new algorithms able to meet these increasing requirements [6], [7].

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Contributions:

- Introducing a new algorithm based on Adaptive Activity Cycling to improve "energy efficiency in Wireless Sensor Networks".
- Comprehensive evaluation for algorithm using real word simulation scenario.
- Comparing the suggested algorithm with other well-known algorithms like LEACH, PEGASIS, S-MAC and T-MAC.
- Explain the benefits of the proposed algorithm "in terms of energy consumption", "network lifetime, packets delivery ratio" and response time.

The rest of paper is section 2 for Related Works, section 3 for Adaptive Activity Cycling Algorithm, section 4 for Evaluation metrics, section 5 for Simulation Scenario and Results, section 6 for Results Visualization, Analysis and Discussion, section 7 for Conclusions and Future Works and the last section is for References.

2. RELATED WORKS

In [8], the research discuss applying the machine learning techniques to "improve energy efficiency" and "extend network lifetime in Wireless Sensor Networks". The researchers explore different algorithms and frameworks, which make the sensors able to make smart decisions about energy using and communicating, which lead to enhance the overall network performance.

In [9], they explore Green Internet of Things concept and how applying it to "improve energy efficiency in Wireless Sensor Networks", with focusing on environmentally friendly technologies and Sustainable applications.

In[10] , this research explores the energy saving clustering protocols which aim to reduce energy consumption in Wireless Sensor Networks due improve clustering operation and the communication among nodes, which contribute to increase network lifetime and improve overall system performance.

In[11] , this research introduces adaptive energy management algorithms, which aim to improve energy distributing among sensor nodes, this is done by adjusting sleep and wake policies dynamically based on network status and application requirements.

In [12], this research discussed the balance between the security and energy efficiency in Wireless Sensor Networks, with focusing on how to achieve high security without negatively affecting energy consumption, due using energy efficient encryption techniques**.**

In [13], this research introduces solutions based on artificial intelligence to improve energy consumption "efficiency in Wireless Sensor Networks", with analyzing the performance of these solutions comparing with traditional techniques, which contribute to improve energy management and prolong network lifetime.

In [14], the research focus on various energy harvesting techniques which can applying it in Wireless Sensor Networks, like solar energy, thermal energy and kinetic energy, focusing on how to improve energy efficiency due taking advantage of environmental energy sources.

In [15], this research deals with access control protocols to energy saving media in Wireless Sensor Networks, with improving the communication among nodes to reduce energy consumption and increase network efficiency.

In [16], they discuss the integrating of Internet of Things with Wireless Sensor Networks in the smart cities, exploring the advantages and challenges which face the achievement of efficient energy management in this context, with introducing innovative solutions to improve operational efficiency and security.

In [17], the research discusses Blockchain technique to improve energy management in Wireless Sensor Networks, focus on how achieve effective and secure energy distribution using distributed encryption techniques. Table 1 summarizes the energy related works briefly from 2007 until now, in an organized manner.

Table 1. - Related works summarization.

Ref. No.	Title	Publisher	Year	Technique Used
[11]	PAS: Prediction-based Adaptive Sleeping for Environment Monitoring in Sensor Networks	IEEE Access	2007	Adaptive Energy Management
[16]	Energy Management in Smart Cities Based on Internet of Things: Peak Demand Reduction and Energy Savings	*Sensors*	2017	IoT Integration
[14]	Energy Harvesting Techniques In Wireless Sensor Networks	*Facta Universitatis*	2018	Energy Harvesting
[8]	An Overview of Machine Learning-Based Energy-Efficient Routing Algorithms in Wireless Sensor Networks	*Electronics (Basel)*	2021	Machine Learning
[12]	Energy Efficient Encryption Algorithm for Wireless Sensor Network	[Online]	2022	Security and Energy Trade-offs
[9]	Green IoT for Eco-Friendly and Sustainable Smart Cities: Future Directions and Opportunities	*Mobile Networks and Applications*	2023	Green IoT
[10]	A Centralized Energy-Efficient Clustering Protocol for Wireless Sensor Networks	*IEEE Sens J*	2023	Energy-Efficient Clustering
[15]	Energy Efficient Medium Access Control Protocol for Wireless Sensor Networks	*(IRSEC)*	2023	Energy-Efficient MAC Protocols
[17]	Blockchain mechanism and symmetric encryption in a wireless sensor network	*Sensors*	2023	Blockchain for Energy Management
[13]	AI-Based Decision Support System Optimizing Wireless Sensor Networks for Consumer Electronics in E-Commerce	*Applied Sciences*	2024	AI-Based Energy Optimization

3. ADAPTIVE ACTIVITY CYCLING ALGORITHM FOR ENERGY MANAGEMENT IN “WIRELESS SENSOR NETWORKS”

“Wireless Sensor Networks (WSNs)” considered as crucial in applications, such as smart agriculture, environmental monitoring and health care. These networks consist of sensing nodes rely on battery, which makes energy management crucial for extending network lifetime. We present an adaptive activity-cycling algorithm for energy management, which depends on node dynamic activity cycles modification. The algorithm relies on “Duty Cycling” concept, where the node turns on for specified period, and then turns it off to save energy, with on and off periods setting according network traffic and battery level. The algorithm performance is evaluated using NS3 and MATLAB simulation tools. The results showed significant enhancements in energy consumption efficiency with maintaining Quality of Service, which makes it suitable for wide range of WSNs applications.

Algorithm steps:

A) Initialization

A1) Preparing nodes in Wireless Sensor Network.
A2) Define basic network standards such as coverage range, update frequency and energy levels.
A3) Specifying initial energy level for each node.

B) Start

For each node in network:
Setup the node to “active state”.

C) Traffic Monitoring

Frequently, for each period (T):
Collect traffic information (number of sent and received packets).

D) Specifying Traffic State

D1) If traffic state is “low”:
Setup on and off periods to “increase off periods”.
D2) If traffic state is “medium”:
Setup on and off periods to “balanced”
D3) If traffic state is “high”:

Setup on and off periods to "decrease off periods".

E) Battery level monitoring

Frequently, for each period (T):

Collect information about battery maintain energy level for each node.

F) Modifying updating periods based on battery level

For each node

If battery level is "low", (lower than specified threshold)

Increase "off periods" to save energy.

If battery level is "medium" (in the range of specified thresholds)

Use balanced duty cycles.

If battery level is "high" (higher than specified threshold)

Decrease "off periods" to ensure data transmitting effectively.

G) Duty Cycles Execution

For each node

Enter the node into an "active state" for the specified period.

Sending and receiving data.

Enter the node in a "dormant state" for the specified period to conserve energy.

H) Repeat the operation

Back to the step "C" frequently.

I) Performance Evaluation

Periodically (every certain period):

Evaluate Quality of Service (Response Time and Packets Delivery Ratio).

Modifying activity-cycling standards based on evaluation to improve performance.

J) Stop

Terminate algorithm.

In the last, this algorithm uses mixing of traffic monitoring and battery level to adapt activity cycles in Wireless Sensor nodes. The goal is achieving balance between energy efficiency and Quality of service, which leads to improve the effectiveness and the network lifetime. Figure 1 visualization of main steps of the algorithm.

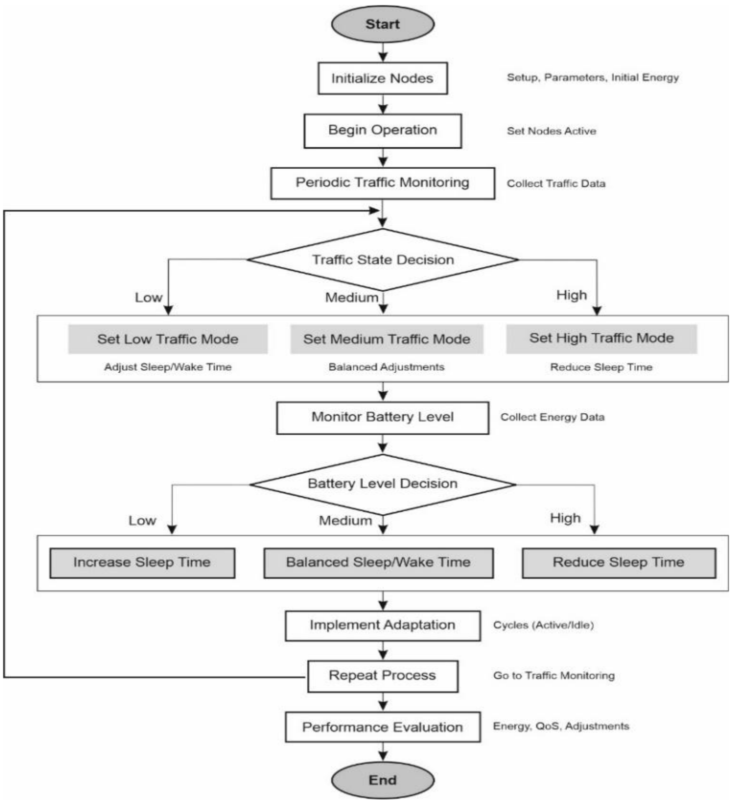

FIGURE 1. - Visually illustrates the main steps of the algorithm.

4. EVALUATION METRICS

Four major metrics was chosen to measure performance of energy management algorithms in “Wireless Sensor Networks (WSNs)”: “energy consumption, network lifetime”, packets delivery ratio (PDR) and response time. These standards provide a comprehensive overview of each algorithm efficiency in terms of energy and resources consumption, its ability to conserve network communication, data delivery efficiency and response time among nodes [18], [19] .

a) **Energy consumption:** measures the average of energy consumed by node for each sending and receiving cycle. Its crucial factor for battery lifetime and the long of node operation time. The efficient algorithm reduces energy consumption to maintain longer battery life, which prolong overall network lifetime. Efficient energy management considered as vital for environments which hard to replace battery or recharge it [20].

b) **Network Lifetime:** Indicates to time period which the network continue operation in it before energy exhaustion of first node. Considered as crucial metric because it is specify total efficiency of network [21]. A network operate for longer time means longer time monitoring and controlling operations without turning off. This metric is important especially for critical operations like environmental monitoring or smart infrastructure [22].

c) **Packet Delivery Ratio (PDR):** it is a packets percentage, which deliver successfully to the final destination. Considered as indicator for data transmission efficiency in network. High percentage delivery means the sensed data arrive to the central station confidently. It is important for to guarantee data confidently and accuracy in different application [23].

d) **Response Time:** It is the average time it takes for a packet to arrive from source to destination. It is indicator for network event response. Low response time is important for applications require quick transmission for data like early warning and immediate monitoring systems. This metric helps to evaluate algorithm ability to provide service in the suitable time [24], [25]

These four evaluation metrics provide comprehensive framework to analyze the efficiency and activity of energy management algorithms in Wireless Sensor Networks. By this metrics, we can specify the strength and weakness points for each algorithm, which contributes to improve network performance and its various applications.

5. SIMULATION SCENARIO AND RESULTS

In this research, comprehensive simulation scenario is designed to evaluate Adaptive Activity Cycling algorithm for energy management in Wireless Sensor Networks (WSNs) with compare it with other algorithms that used for same field. The goal from this simulation is to provide a uniform environment that make us able to analyze different energy efficiency sides and Quality of service produced by each algorithm. The scenario is prepared on 100m X 100m area; contain 100 sensor nodes distributed randomly. Each node begin by initial energy of 2 joules, and communicate with each other’s by communication range of 15m. The sent packet size is specified by 512 Byte, the simulation time continue for 1000sec. We are used Constant Bit Rate (CBR) model to generate packets by constant average in each second. The sensor nodes are considered as constant in its positions through simulation period, which can focus on energy consumption that related to sending and receiving instead of mobility. The energy consumption rates are specified by 50 Nano Joule for each sent or received bit, with lower energy consumption in idle and sleep states (0.01 mW and 0.001 mW respectively). The simulation depended on Media Access Control (MAC) IEEE 802.11 protocol, which provide efficient management to access wireless media. In addition, AODV “(Ad-hoc On-Demand Distance Vector) protocol” is used to specify the routs among nodes dynamically. This scenario provide integrated simulation environment to analyze Adaptive Activity Cycling algorithm comparing with other algorithms such as LEACH, PEGASIS, S-MAC and T-MAC. Through this simulation, we can produce subjective and comprehensive evaluation for efficiency of each algorithm in improving energy management and guarantee Quality of Service in Wireless Sensor Networks. Table 2 provides comprehensive used parameters values. Table 3 shows the simulation results for the scenario in Table 2.

Table 2. - Simulation Scenario.

Parameter	Value
Network Area	100m x 100m
Number of Nodes	100
Initial Energy per Node	2 Joules
Transmission Range	15 meters
Packet Size	512 bytes
Simulation Time	1000 seconds

Traffic Model	Constant Bit Rate (CBR)
Packet Generation Interval	1 second
Mobility Model	Static Nodes
Energy Consumption (Tx/Rx)	50 nJ/bit (Transmit/Receive)
Idle Power Consumption	0.01 mW
Sleep Power Consumption	0.001 mW
MAC Protocol	IEEE 802.11
“Routing Protocol”	“AODV (Ad hoc On-Demand Distance Vector)”
Evaluation Metrics	“Energy Consumption, Network Lifetime, Packet Delivery Ratio,” Response Time
Simulation Tool	NS-3 (Network Simulator 3)

Table 3. - Performance Comparison for Energy Management Algorithms in WSNs

Algorithm	Energy Consumption (mJ)	Network Lifetime (days)	Packet Delivery Ratio (%)	Response Time (ms)	Scalability	Complexity
Adaptive Activity Cycling	2.5	180	95	50	High	Medium
LEACH	3.0	150	90	70	Medium	Medium
PEGASIS	2.8	160	92	90	Low	High
S-MAC	3.5	140	88	100	Medium	Low
T-MAC	3.2	145	89	80	Medium	Medium

6. RESULTS VISUALIZATION, ANALYSIS AND DISCUSSION

- **Energy Consumption**

Adaptive Activity Cycling Algorithm recorded lower energy consumption by average 2.5mJ for each sending cycle, which leads to its activity in term of energy consumption reduction compared with others. This makes it suitable for using in the networks that required effective energy management to conserve battery lifetime for longer periods. Figure 2 is a chart for the Energy Consumption Visualization.

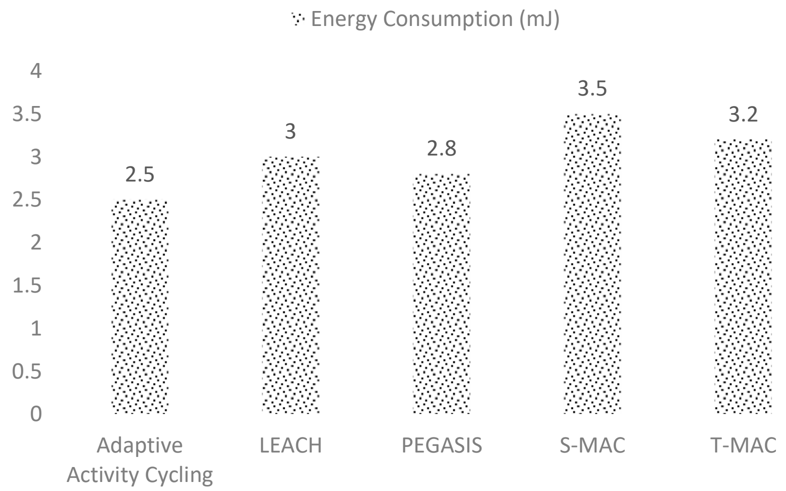

FIGURE 2. - Energy Consumption Visualization.

- **Network Lifetime**

The results shows, the Adaptive Activity Cycling Algorithm contributes to prolong network lifetime to 180 days, which is the highest among all the algorithms under the study. This reflects the algorithm efficiency in energy consumption contributed equally among nodes, which reduces battery exhaustion rate and guarantee operates the network for longer period. In contrast, the S-MAC algorithm recorded the lowest network lifetime at 140 days. Which indicates to non-optimal energy consumption may affect negatively on network lifetime continuity. Figure 3 is a chart for the Network Lifetime Visualization.

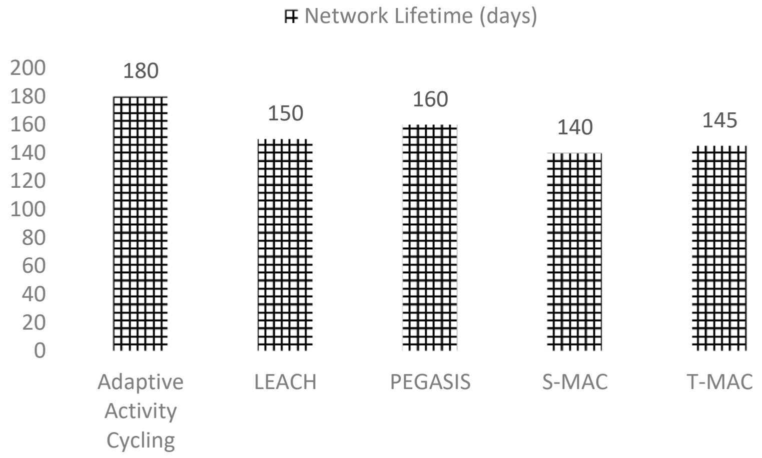

FIGURE 3. - Network Lifetime Visualization.

- **Packet Delivery Ratio (PDR)**

Adaptive Activity Cycling Algorithm achieved highest Packet Delivery Ratio at 95% rate, which indicates to it is confidentially to transmit data without significant packets losing. This support received data accuracy and guarantee deliver important information to the central station. With comparison, S-MAC algorithm recorded lowest Packets Delivery Ratio at 88%, which is may leads to data losing and thus decrease collected information accuracy. Figure 4 is a chart for the PDR Visualization.

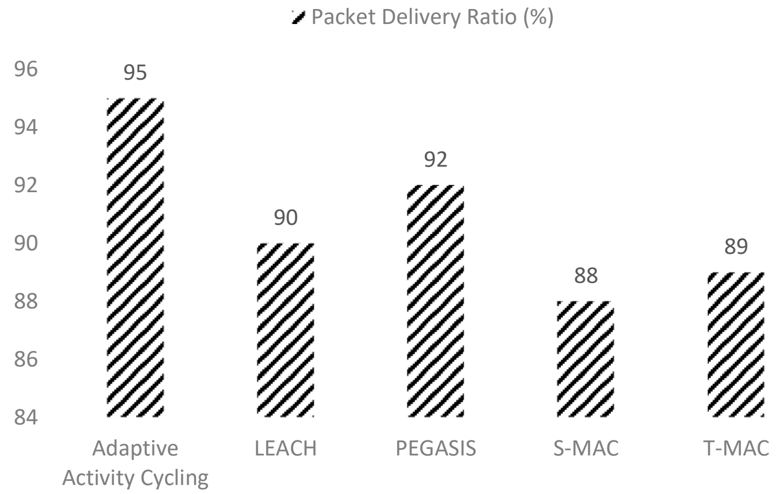

FIGURE 4. - PDR Visualization.

- **Response Time**

The Adaptive Activity Cycling Algorithm recorded response time 50ms, which is a shortest time among the algorithms in comparison, which makes it suitable for applications that required quick response for events. S-MAC algorithm recorded longest response time is 100ms, which is may limit their effectivity in immediate applications, which need for quick data transmission. Figure 5 is a chart for the Response Time Visualization.

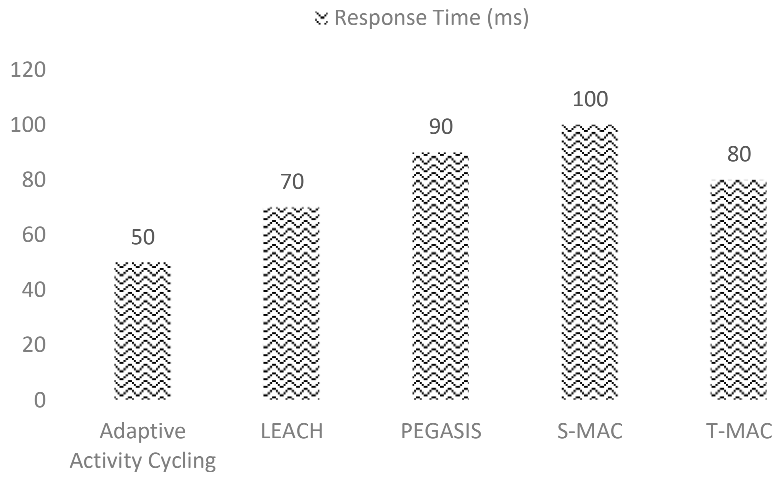

FIGURE 5. - Response Time Visualization.

- **Scalability and Complexity**

  The results show the Adaptive Activity Cycling Algorithm has high scalability, which makes it able to maintain its performance with increasing network size. The medium complexity of algorithm makes it balance between performance and executing efficiency. With comparison, PEGASIS algorithm has low scalability and high complexity, which may hinder its use in large and complex networks. Figure 6 is a chart for the Scalability and Complexity Visualization.

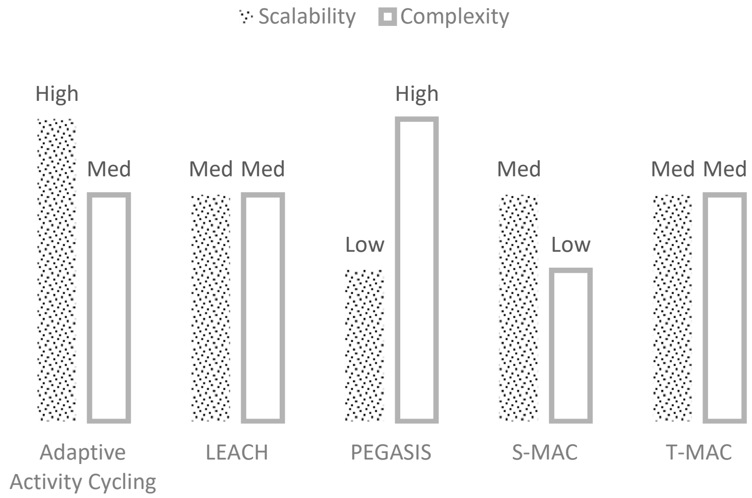

FIGURE 6. - Scalability and Complexity Visualization.

7. CONCLUSIONS AND FUTURE WORKS

In this research, we have produced and evaluated the Adaptive Activity Cycling Algorithm for energy management in Wireless Sensor Networks (WSNs). The main goal was improving energy efficiency, prolong network lifetime, and with addition to ensure confident data transmission with maintain low response time. The comparison is done between the suggested algorithm and the well-known energy management algorithms, like LEACH, PEGASIS, S-MAC and T-MAC using comprehensive simulation scenario. The simulation results showed the Adaptive Activity Cycling Algorithm excels greatly the other algorithms on several key metrics. Firstly, it showed the lowest power consumption of 2.5mJ for each cycle, which highlights its high efficiency to maintain battery lifetime. This efficiency directly translated to prolong network lifetime to achieve 180 days, which is the longest among compared algorithms, which indicates to its activity to conserve network operations for long periods.

Furthermore, the Adaptive Activity Cycling Algorithm achieved highest packets delivery ratio of 95%, which guarantee delver most of data packets to its destination with high confidently. This high ratio for packets delivery considered vital for the applications that required precise and continues data aggregation, like environmental monitoring and precise agriculture. In addition to, the algorithm maintained low response time of 50ms, thus makes it suitable for immediate applications that require quick data transmission and quick response. The scalability and medium complexity of Adaptive Activity Cycling Algorithm confirm its particularity to apply it in different Wireless Sensor Networks applications. Unlike PEGASIS, which despite its low power consumption, its suffer from high response time and great complexity, so our algorithm achieve balance between performance and execution ability. In conclusion, our algorithm produce strong solution to support energy management in WSNs. Its ability to modify activity cycle's dynamically based on network environment guarantee optimal using the energy without effecting to the data confidentiality or data transmission speed. This balance makes the algorithm significantly suitable for wide collection of WSNs applications, especially those where energy conservation and data integrity are crucial. The future works can explore further improvements and real word deployment scenarios to diagnose these results and expand it.

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CONFLICTS OF INTEREST

The author declares no conflict of interest

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