ENERGY OPTIMIZATION IN WIRELESS SENSOR NETWORKS FOR FOREST FIRE DETECTION: A STUDY OF SLEEP SCHEDULING TECHNIQUES

Manar Khalid Ibraheem, Mbarka Belhaj Mohamed and Ahmed Fakhfakh

Laboratory of signals, systems, Artificial intelligence and Networks (SM@RTS), Digital Research Center of Sfax (CRNS).

ABSTRACT

Wireless Sensor Networks (WSNs) have gained significant interest in forest fire applications due to their potential for real-time monitoring, early detection, and quick reaction. However, energy consumption poses a challenge as sensor nodes primarily rely on batteries. Efficient energy management is crucial to extend network lifespan, reduce maintenance frequency, and ensure continuous monitoring. This paper proposes the use of sleep-based concepts in WSNs for forest fire detection to optimize energy consumption. The study utilizes the Omnet++ simulation platform to model and simulate a realistic WSN deployed in a forest fire detection scenario. It analyses power consumption patterns, evaluates different MAC protocols, and explores sleep scheduling optimization.

KEYWORDS

Forest fires, Wireless sensor networks (WSNs), Energy consumption, Sleep mode& Omnet++

1. INTRODUCTION

The potential of wireless sensor networks to perform real-time monitoring, early detection, and quick reaction has attracted a lot of interest in forest fire applications [1]. Many small sensor nodes, each with its own sensing, processing, and communication capabilities, make up a WSN. A dispersed network formed by these nodes allows for the effective collection and transmission of data from far-flung locations. In the context of forest fire applications, WSNs may be set up in high-risk areas to track environmental factors like temperature, humidity, and smoke to aid in early identification and effective mitigation efforts.

In WSNs, energy consumption is of paramount importance since most sensor nodes run on batteries. To extend the network's useful life, reduce the frequency of required maintenance, and guarantee continuous monitoring and detection, its operation must be as energy-efficient as possible [2]. However, there are a number of obstacles to efficiently regulating energy consumption due to the limited resources of sensor nodes and the need for constant data transmission and processing.

When monitoring for forest fires using WSNs, energy efficiency is crucial. Nodes must rely on battery power because of the unreliability of electricity in forested regions. The sensor nodes'

David C. Wyld et al. (Eds): CMLA, GRAPH-HOC, CIoT, DMSE, ArIT, WiMoNe, CSEIT – 2023
pp. 49-61, 2023. CS & IT - CSCP 2023 DOI: 10.5121/csit.2023.131005

energy consumption habits have a direct bearing on how long they can keep working [3]. Therefore, managing energy usage may increase the effectiveness of forest fire detection networks, lengthen the lifespan of the network, and lower the frequency with which batteries must be replaced.

The use of sleep-based ideas has shown promise as a strategy for overcoming the difficulties associated with energy usage in WSNs. Energy may be saved during times of inactivity by properly arranging the sleep and active periods of sensor nodes. By taking use of the fact that not all nodes must be operational at once, this method facilitates adaptive power management and load balancing. Reduced energy consumption may be achieved without degrading network performance by the strategic cycling of nodes between sleep and active states.

For efficient energy management in WSNs, it is necessary to understand the power consumption variances between sleep mode and active mode. Identifying the key contributors to energy consumption and developing energy-efficient protocols and algorithms requires assessing the energy consumption patterns of sensor nodes during different operating stages. Finding the ideal ratio of inactive to active time and developing methods to dynamically adjust to network circumstances may be achieved by analyzing power usage disparities.

In this research, we will employ the Omnet++ simulation platform to model and simulate a wireless sensor network deployed for forest fire detection. By integrating sleep-based concepts and analysing power consumption differences, we aim to gain insights into energy optimization strategies that can enhance the performance, reliability, and longevity of WSNs within forest fire applications.

Our research goals need an intensive investigation of how energy is used by WSNs put into service to monitor for forest fires. We will look at how variables like network size, node density, data transmission speeds, and sleep-to-active ratios affect energy use. By considering these elements, we can find the best setup for reducing energy use without sacrificing effectiveness in detecting forest fires.

The Omnet++ simulation platform will be an invaluable resource for our study. To effectively describe the features and difficulties of forest fire detection situations, we will construct and simulate a realistic WSN model. By simulating real-world situations and taking into account variables like node mobility, environmental changes, and data processing needs, we can provide accurate findings that are reflective of the energy consumption patterns in actual installations.

In addition, we will be evaluating and developing protocols and algorithms that minimize energy use. We'll look at methods like data aggregation, adaptive sleep scheduling, and routing optimization that have already been used to reduce energy consumption and boost networks' overall effectiveness. By including these methods into our simulation model, we can evaluate how well they work to decrease energy use while keeping data quality and timeliness at acceptable levels.

Significant implications for the design, deployment, and operation of WSNs for forest fire applications are expected to arise from this study's research results. The information gleaned will be used to create techniques that use less energy, so extending the network's lifespan, decreasing maintenance costs, and improving the system's ability to detect forest fires. By reducing power usage, WSNs may remain in service for longer without losing their capacity to quickly identify and react to forest fires.

The rest of the paper will be structured as follows: Section II reviews the time-scheduling methods used in WSN for sleeping. Section III describes some MAC protocols used in WSN.

Section IV gives a review of the related work. Section V describes the simulation and experiments.

2. TIME-SCHEDULING METHODS FOR SLEEP

In wireless sensor networks (WSNs) used to detect forest fires, sleep scheduling is an essential part of energy management. Sleep scheduling strategies strive to reduce power consumption while maintaining the required performance of a network of sensor nodes by synchronizing their sleep and waking times. This discussion of sleep scheduling approaches and their role in attaining energy efficiency in WSNs serves as an introduction to the topic.

2.1. Synchronized Sleep Scheduling

The term "synchronized sleep scheduling" refers to the process of synchronizing the rest times of individual sensor nodes across a network. In this method, nodes are organized into clusters, and the wake-up and sleep cycles of the nodes inside a cluster are coordinated by a cluster head. This synchronization makes sure that at any one moment, only a small percentage of nodes are actively processing data, while the rest go into sleep mode to save power.

Low-Energy Adaptive Clustering Hierarchy (LEACH) is a popular mechanism for coordinating sleep times among several devices. To reduce spikes in energy consumption and ensure that resources are used efficiently throughout the network, LEACH uses dynamic cluster head selection and cluster head role rotation. Effectively lowering energy usage and increasing network lifespan, this method has been used in forest fire detection situations [4].

2.2. Asynchronous Sleep Scheduling

Asynchronous sleep scheduling, often known as duty cycle, is a method through which nodes may function autonomously without any requirement for central coordination. Each node sets its own schedule for when it sleeps and when it wakes up, using either its own internal data or a set of duty cycle parameters. This method enables nodes to save energy in a way that best suits their needs and adapts to the dynamic nature of networks.

Adaptive duty cycling is a method of asynchronous sleep scheduling that dynamically modifies the duty cycle in response to external influences and data gathering requirements. To better balance energy efficiency and data quality. Nodes may save power during times of inactivity while yet responding quickly to urgent situations by altering their sleep and active cycles [5].

2.3. Hybrid Sleep Scheduling

Hybrid sleep scheduling strategies maximize energy usage in WSNs by combining synchronized and unsynchronized procedures. This combined strategy draws on the best features of both approaches to maximize energy savings while maintaining network responsiveness.

Hierarchical sleep scheduling, for instance, combines synchronized sleep scheduling across clusters with decentralized scheduling for individual nodes. Cluster leaders coordinate their sleep cycles, whereas individual nodes within a cluster set their own timetables for when to go to sleep and when to wake up. This method saves energy by optimizing communication between nodes and controlling how often they're active.

WSNs for forest fire detection rely heavily on sleep scheduling strategies for maximizing network lifespan and minimizing energy use. These methods allow sensor nodes to preserve energy during times of low activity while still responding to fire events by precisely selecting when to sleep and when to wake up. Considerations such as network structure, data collecting needs, and the intended trade-off between energy usage and network responsiveness should inform the choice of sleep scheduling strategy. In order to further enhance energy economy in forest fire detection.

3. MAC PROTOCOLS

MAC protocols differ in their approach to managing access to the wireless medium and optimizing energy consumption in wireless sensor networks. Each protocol has its own advantages and trade-offs, making it important to evaluate and select the most suitable protocol based on the specific requirements and constraints of the network application.

3.1. TMAC (Time Division Multiple Access)

TMAC is a MAC protocol that uses time division multiple access techniques to allocate time slots to different nodes in a network. Each node is assigned a specific time slot during which it can transmit data. TMAC ensures that only one node transmits at a time to prevent collisions and ensure efficient data transmission.

3.2. TumbleMAC

TumbleMAC is a MAC protocol designed for wireless sensor networks. It is based on the idea of sleep-wake scheduling, where nodes alternate between active and sleep periods to conserve energy. TumbleMAC uses a randomized sleep schedule, allowing nodes to sleep for varying durations to minimize collisions and maximize network efficiency.

3.3. BypassMAC

BypassMAC is a MAC protocol that aims to minimize energy consumption in wireless sensor networks. It achieves this by allowing nodes to bypass the traditional MAC layer and directly transmit data to the sink node, reducing the overhead associated with MAC layer operations. BypassMAC eliminates the need for contention-based access methods and focuses on energy efficiency in data transmission.

4. RELATED WORK

The study [6] provides an overview of wireless sensor networks (WSNs) for forest fire detection, emphasizing the importance of timely and accurate data collection. The authors discuss the challenges associated with energy consumption in WSNs and highlight the need for efficient energy management techniques to prolong the lifespan of sensor nodes.

The study [7] proposes an optimized data collection mechanism for forest fire detection using WSNs. The study evaluates the performance of different routing protocols and presents an adaptive duty cycle approach to reduce energy consumption. The findings demonstrate significant energy savings while maintaining the required data collection accuracy.

The survey [8] explores energy-efficient routing protocols for WSNs, including those applicable to forest fire detection. The paper reviews different routing strategies, such as hierarchical and clustering-based protocols, and analyzes their impact on energy consumption. The findings contribute to understanding the trade-offs between routing overhead, network lifetime, and energy efficiency.

Due to its wide range of uses in fields including environmental monitoring, healthcare, and home automation, Wireless Sensor Networks (WSNs), a new technology, have attracted interest. Due to the constrained energy resources of the sensor nodes, WSN energy efficiency presents a substantial issue. As a result, a number of strategies have been put out to increase the energy efficiency of WSNs, including the sleeping strategy [9].

A common method of energy saving utilized in WSNs is sleeping. With this method, sensor nodes are regularly put into a low-power sleep mode to save energy. Typically, the requirements of the application and the state of the network are used to determine the sleep intervals and length of the sleep state. The sensor nodes reduce their power usage and stop processing data, sending, or receiving messages when in the sleep state. With this method, sensor nodes may save energy and extend the life of their batteries.

A preamble sampling-based TR-MAC protocol with a traffic-adaptive duty cycle adjustment mechanism was recommended by the authors of [10].

The authors in [11] presented the traffic-based energy efficient MAC (TBEMAC) protocol, which includes two stages: the duty cycle adjustment phase and the wakeup scheduling phase. Based on traffic volume, buffer health, and sensor node battery life, TBEMAC modifies duty cycle. Based on their battery life and traffic load, this protocol arranges nodes for the awakening phase. The nodes enter sleep mode if there is no communication during the active time.

The traffic adaptive synchronous (TAS) MAC protocol was developed by the authors of [8] to assist with the duty cycle method and achieve high throughput, low latency, and minimal power consumption. The TASMAC protocol uses TDMA with a state-of-the-art traffic adaptive allocation algorithm that only assigns time slots to nodes on active routes. This protocol proactively modifies the wakeup timings of all the nodes on active routes of incoming data in order to avoid end-to-end delays. The TASMAC separates traffic notification and data transmission scheduling into two stages to accomplish traffic adaptation.

The link between energy consumption, packet loss ratio, and WSN lifespan was investigated by the authors of [12]. The region near to the sink consumes more energy, which is why the authors created the residual energy aware with adjustable duty cycle (READC) protocol.

The authors devised a technique for duty-cycle modulation for WSNs in [13]. Before attempting to determine the appropriate sleep time, the authors first constructed a packet prediction model, then a multi-objective optimisation function for energy usage and latency. The authors of [14] published a novel management approach for the duty cycle-based MAC protocol for WSNs. The first half of the duty cycle, which is divided into two parts by this method, is used for sending or receiving data from one's own neighbour node.

The authors of [15] introduced the EAMP-AIDC protocol, which is based on individual duty cycle optimization, for energy-harvesting wireless sensor networks (EH-WSNs).

The authors created the efficient context-aware multi-hop broadcasting (E-ECAB) protocol in order to maximize resource use and satisfy application requirements [16]. A duty-cycle methodology and other criteria are used by the E-ECAB.

The authors of [17] recommended the multi-mode sensor MAC (MMSMAC), a multi-mode medium access protocol, for latency and energy awareness in WSNs. Synchronization, asynchronous, and hybrid are the three different operating modes for the MMSMAC protocol.

The emergence medium access control (E-MAC) system developed by the authors of [18] was influenced by biological social populations. According to the author, the E-MAC protocol outperformed the IEEE 802.11 CAMA/CA standard in terms of performance.

The authors of [19] recommended the adaptive intelligent hybrid medium access control protocol (AI-HMAC) for low power duty cycle WSNs. The AI-HMAC protocol employs the technique, which is based on mixed TDMA and CSMA-based traffic. The main objective of this protocol is to modify IH-MAC's link scheduling and use windows techniques.

5. SIMULATION AND EXPERIMENTS

To evaluate the effectiveness of the proposed approach and examine the influence of energy consumption on a Wireless Sensor Network (WSN) for forest fire detection, a series of simulations and experiments were conducted. The simulations were carried out using the Omnet++ 4.6 simulation program with the Castalia 3.3 framework. The network model is described in Figure 1.

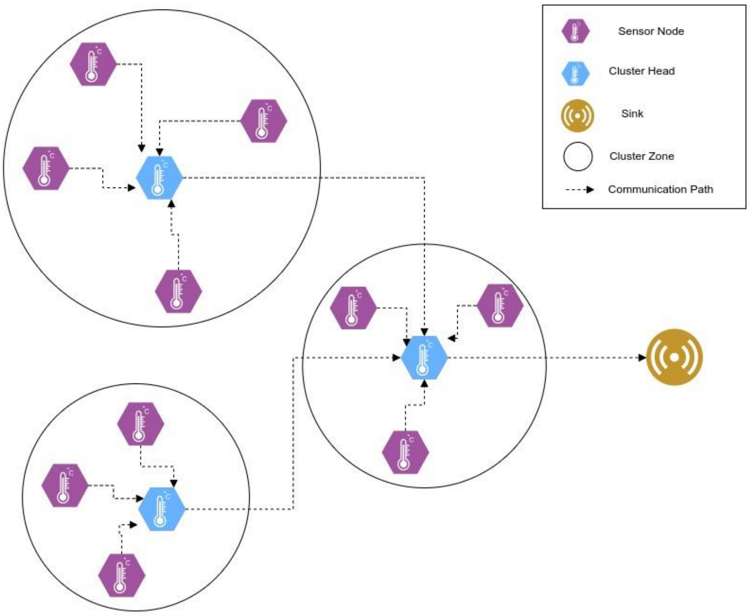

Figure 1: Network Model.

The experiments consisted of two parts:

- Experiment 1: The objective of this experiment was to determine the most energy-efficient MAC (Media Access Control) communication protocol for the WSN. Various MAC protocols were compared to assess their power consumption. The simulations were designed to measure and compare the energy consumption of different MAC protocols under the given conditions.
- Experiment 2: Following the selection of the optimal MAC protocol from the first experiment, the second experiment aimed to identify the best configuration settings for the chosen MAC protocol. This involved adjusting and testing different parameters

related to the selected MAC protocol to optimize its performance and energy efficiency within the WSN.

By conducting these simulations and experiments, we were able to evaluate the proposed approach, determine the most energy-efficient MAC protocol for the WSN, and further optimize its configuration settings. These findings contribute to enhancing the efficiency and effectiveness of the WSN in forest fire detection.

5.1. Experiment 1

In this experiment, we compared the power consumption of a network that uses different mac communication protocols to determine which protocol consumes the least energy. The network was prepared according to the parameters shown in Table 1.

Table 1. The network parameters for First Experiment.

Parameter	Value
Initial Energy	18720 Jol
Simulation Time	2000 ms
Nodes	50
Field Range	200 * 200 square meter
Mac	TumbleMAC, TMAC, BypassMAC
Round Length	5 seconds

It is evident from the results in Figure 2 and Table 2 that TumbleMAC has the lowest power consumption with a value of 87.51909. TMAC follows closely with a power consumption of 89.23338, while BypassMAC consumes the most power with a value of 135.9985.

Therefore, based on this data, TumbleMAC would be the protocol, which consumes the least energy among the three protocols that tested in our experiment.

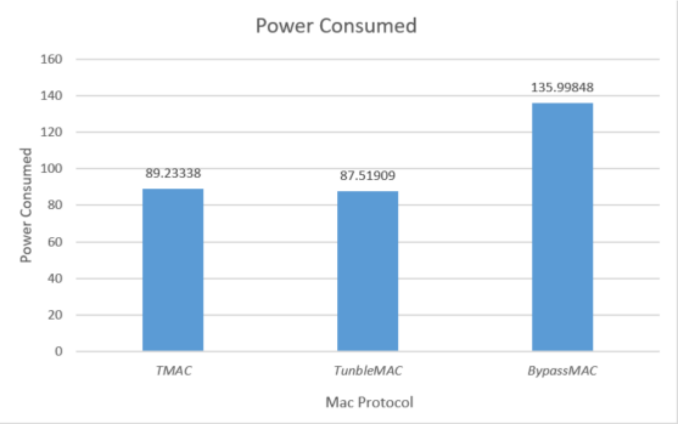

Figure 2. Comparison between the powers consumed for different Mac protocols.

Table 2. Power consumed for different Mac protocols.

MACProtocol	Power Consumed
TMAC	89.23338
TumbleMAC	87.51909
BypassMAC	135.9985

5.2. Experiment 2

In this experiment, the objective was to adjust the sleep settings in the TumbleMAC protocol to find the optimal value for the duty cycle. The network parameters are described in Table 3. The simulation was conducted according to three scenarios. The scenarios differ from each other in terms of the number of nodes. The number of nodes is 50, 100 and 150 nodes, respectively, in order to take into account the dynamic environment for forest fire application. The nodes are deployed in the network uniformly. As for the model of sending messages used, it depends on measuring the temperature in each node. When the temperature rises above a certain threshold, the node generates a message and sends it to the sink.

Table 3. The network parameters for Second Experiment.

Parameter	**Value**
Initial Energy	18720 Jol
Simulation Time	2000 ms
Nodes	50, 100, 150
Field Range	200 * 200 square meter
Mac	TumbleMAC
Round Length	5 seconds

5.2.1. Scenario One

In this scenario, 50 sensor nodes were deployed, with one designated as the sink node. The simulation settings were configured according to the parameters outlined in Table 3. The simulations were conducted for a duration of 2000 seconds, allowing sufficient time to observe the network's performance and energy consumption patterns. Each sensor node started with an initial energy of 18720 Jol.

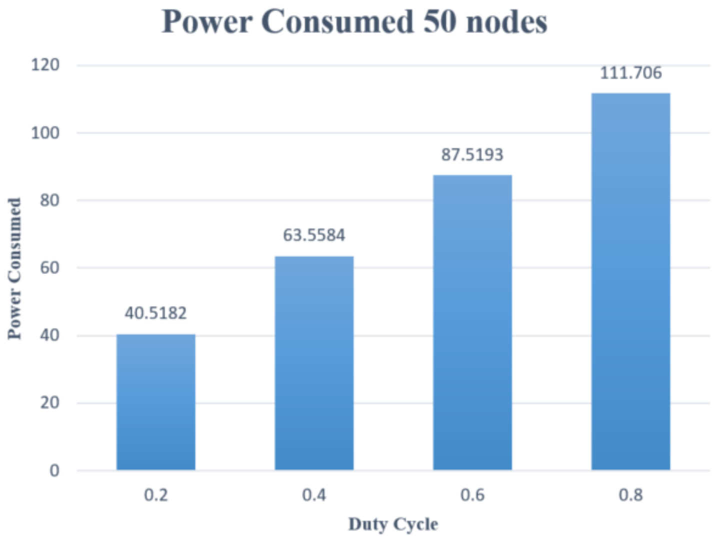

Figure 3. Power Consumed for different duty cycle in Scenario One (50 nodes).

Figures 3 and 4 present the power consumed and remaining energy for Scenario one with 50 nodes, varying duty cycle values. The power consumed increases as the duty cycle increases, with the highest power consumption observed at duty cycle 0.8. Similarly, the remaining energy decreases as the duty cycle increases, indicating higher energy depletion.

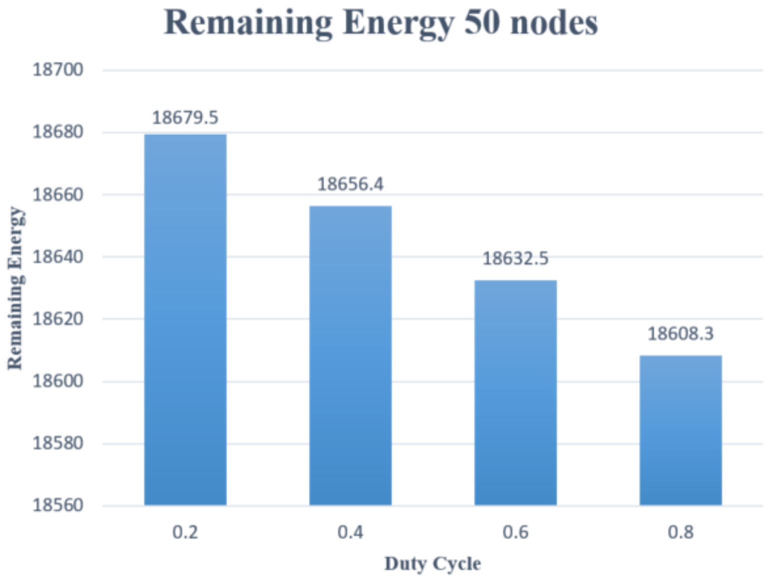

Figure 4. Remaining Energy for different duty cycle in Scenario One (50 nodes).

5.2.2. Scenario Two

In this scenario, 100 sensor nodes were deployed, with one acting as the sink node, within the same work environment as scenario one. The simulation settings and parameters remained consistent with scenario one, enabling a comparative analysis of the network's behaviour and energy consumption patterns with an increased number of nodes.

The power consumed and remaining energy have been calculated as shown in Figures 5 and 6. As observed, the power consumed follows a similar trend as in Scenario one, increasing with higher duty cycles. However, the differences in power consumption between duty cycles are relatively small. The remaining energy also shows a slight decrease with increasing duty cycles.

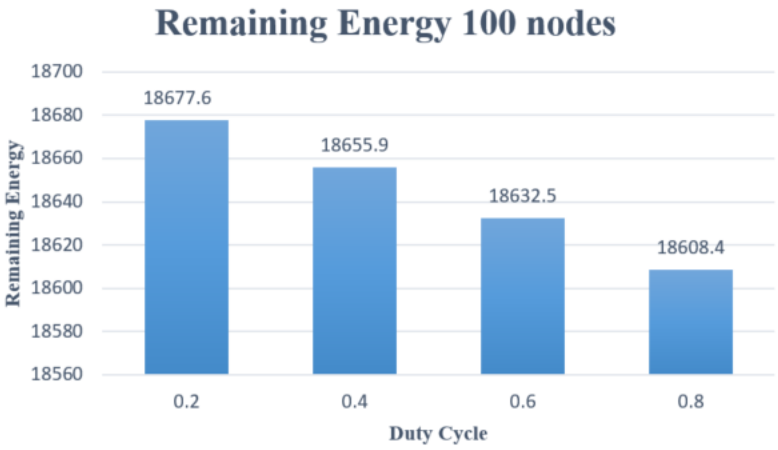

Figure 5. Power Consumed for different duty cycle in Scenario Two (100 nodes).

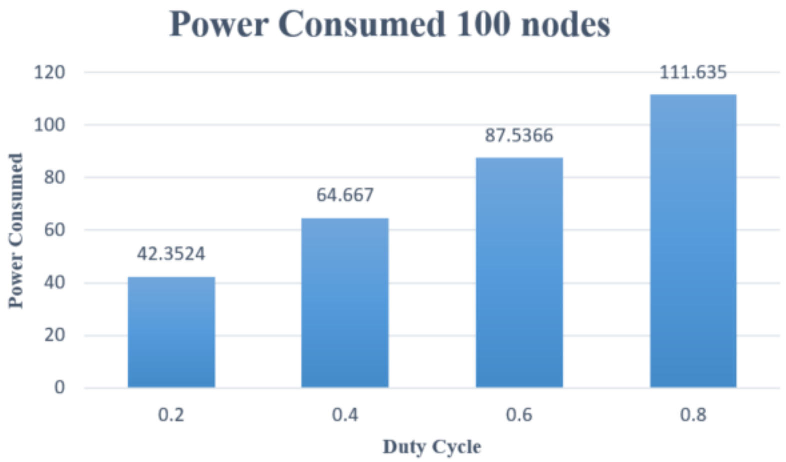

Figure 6. Remaining Energy for different duty cycle in Scenario Two (100 nodes).

5.2.3. Scenario Three

The third scenario involved the deployment of 150 sensor nodes, including one sink node, within the same work environment as scenarios one and two. Similar to the previous scenarios, the simulation settings and parameters were kept constant to observe the impact of a larger network size on energy consumption and overall network performance.

Figures 7 and 8 displays the power consumed and remaining energy for Scenario 3 with 150 nodes. Similar to the previous scenarios, the power consumed increases with higher duty cycles, with duty cycle 0.8 resulting in the highest consumption. The remaining energy decreases with increasing duty cycles, indicating higher energy depletion.

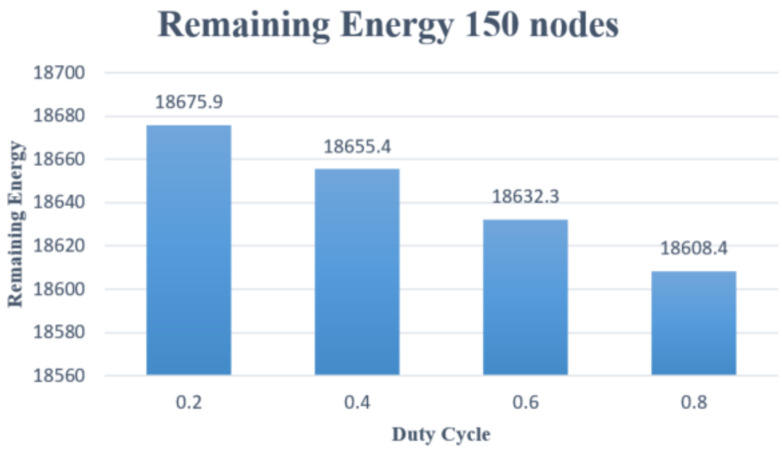

Figure 7. Power Consumed for different duty cycle in Scenario Three (150 nodes).

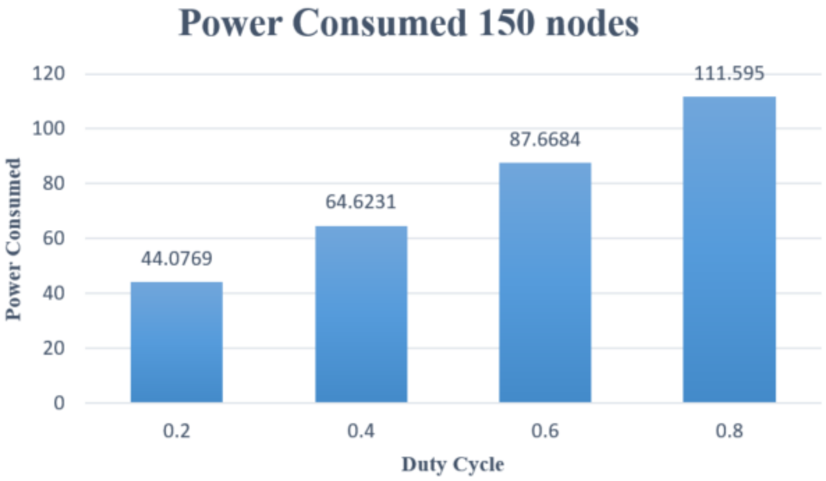

Figure 8. Remaining Energy for different duty cycle in Scenario Three (150 nodes).

The results obtained from the three scenarios demonstrate the relationship between duty cycles, power consumption, and remaining energy in wireless sensor networks.

The results indicate that increasing the duty cycle leads to higher power consumption and decreased remaining energy. This finding highlights the trade-off between data transfer efficiency and energy conservation. It suggests that selecting an optimal duty cycle value, such as 0.6, can strike a balance between energy savings and data transmission delays.

On the one hand, comparing the scenarios with different numbers of nodes, it is observed that larger networks generally exhibit slightly higher power consumption. This can be attributed to increased data traffic and processing requirements. However, the impact on remaining energy is relatively consistent across scenarios.

The contribution of this simulation study lies in its practical implications for energy-efficient forest fire detection systems. By understanding the relationship between duty cycle values, power consumption, and remaining energy, researchers and practitioners can design more effective protocols and algorithms for prolonging the lifespan of sensor nodes and optimizing network stability. Additionally, the simulation results provide a quantitative assessment of energy consumption, which can aid in decision-making and resource allocation for deploying and maintaining wireless sensor networks in forest fire detection applications.

The proposed system for wireless sensor networks (WSNs) in forest fire detection exhibited certain limitations and deficiencies during testing and evaluation. These include the simplified network model used, which may not fully represent real-world complexities, and the assumption of homogeneous nodes, which may differ in capabilities and energy levels. The duty cycle optimization and lack of real-world deployment validation further highlight areas for improvement. Despite these limitations, the conducted simulations and experiments provide valuable insights for further research and development to address the complexities of real-world deployments.

This simulation study serves as a useful tool for evaluating and optimizing the energy efficiency of wireless sensor networks in forest fire detection. The findings contribute to the ongoing efforts in developing sustainable and effective monitoring systems to mitigate the impact of forest fires.

6. CONCLUSIONS

The purpose of this research is to examine the complex interplay between energy use and performance in wireless sensor networks (WSNs) designed to detect forest fires. By using sleep-based concepts and analysing changes in power use, we want to maximize power economy and boost the efficiency of forest fire monitoring systems. Research findings might lead to more reliable networks, longer lifespans for sensor nodes, and less damage from forest fires if used to the design of new energy-efficient protocols, algorithms, and approaches.

Finding that sweet spot between fast data transfer and low power consumption is crucial to the widespread use of WSNs for forest fire monitoring. Because of the unreliability of electricity in forested areas, sensor nodes that run on batteries are typically used. In order to keep these nodes running for as long as possible, with as little downtime for maintenance and interruptions in monitoring as possible, it is essential that their energy consumption be managed and optimized. By solving the problem of energy consumption, we can make forest fire monitoring systems more effective and trustworthy.

The results of this study have important implications for how WSNs are planned, implemented, and managed during forest fires. The knowledge gathered will allow for the creation of protocols, algorithms, and tactics that are less taxing on the network's energy supply, which in turn will increase the lifespan of sensor nodes, strengthen the dependability of the network, and lessen the impact of forest fires. Our findings and suggestions, gleaned from our work with the Omnet++ simulation platform, will be invaluable to researchers and practitioners in the fields of wireless sensor networks and forest fire management. We want to aid the development of long-term, reliable forest fire monitoring systems that may save lives, habitats, and species by focusing on the pressing problem of energy consumption.

In future work, several areas can be explored to enhance the effectiveness of the research. Real-world deployment validation would provide valuable insights into the system's performance and reliability in practical forest fire monitoring scenarios. Adaptive duty cycle optimization algorithms can be developed to dynamically adjust energy consumption based on real-time network conditions.

ACKNOWLEDGEMENTS

We would like to express our deepest gratitude to every individual who has contributed to the completion of this project.

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