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Performance Evaluation of 5G Networks using Fixed, Adaptive and Threshold based Duty Cycle Adjustment for Wireless Sensor Networks

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Abstract: - Wireless Sensor Networks (WSNs) hold immense potential for diverse applications, ranging from environmental monitoring to industrial automation. In the context of the impending 5G revolution, the convergence of WSNs and 5G networks offers new possibilities for efficient data transmission and communication. A crucial aspect of WSNs is duty cycling, where sensor nodes alternate between active and sleep modes to conserve energy. This research delves into the performance evaluation of three distinct duty cycles adjustment strategies Fixed, Adaptive, and Threshold-based in the context of 5G-enabled WSNs. In this study, we design and simulate an experimental framework that integrates the dynamics of 5G networks and the nuanced behaviors of WSNs. The Fixed Duty Cycle strategy adheres to a predefined duty cycle, while the Adaptive Duty Cycle strategy dynamically adjusts duty cycles based on real-time data rate observations. The Threshold-based Duty Cycle strategy, on the other hand, leverages a threshold to determine the appropriate duty cycle adjustment. Through extensive simulations and analysis, we assess these strategies across multiple performance metrics, including energy efficiency, packet delivery ratio, data rate, and throughput. The obtained results reveal nuanced trade-offs among the strategies, offering insights into their suitability for various application scenarios. Our findings underscore the importance of context-aware duty cycle adaptation in optimizing the performance of 5G-enabled WSNs, while respecting the energy constraints inherent to sensor nodes. This research contributes to the growing body of knowledge in the realm of 5G-WSN convergence and offers practical insights for designers, engineers, and researchers seeking to harness the full potential of these technologies. By comprehensively evaluating the implications of duty cycle adjustment strategies, this work contributes to advancing the efficiency and applicability of 5G networks in the realm of Wireless Sensor Networks.

Keywords: Wireless Sensor Networks, 5G Networks, Duty Cycle Adjustment Strategies, Energy Efficiency, Packet Delivery Ratio, Data Rate, Throughput.

1. Introduction:

Wireless Sensor Networks (WSNs) have emerged as a transformative technology, enabling pervasive data collection and monitoring across a diverse array of applications. Ranging from environmental sensing to industrial automation, the deployment of WSNs offers unprecedented insights into the physical world, making them indispensable tools for modern society. However, the efficient operation of these networks hinges on addressing fundamental challenges such as energy efficiency, data reliability, and communication latency. In recent years, the evolution of communication networks, particularly the advent of fifth-generation (5G) networks, has brought forth a new horizon of possibilities for WSNs. With their promise of high data rates, ultra-reliable low-latency communication, and seamless connectivity, 5G networks hold the potential to reshape the dynamics of WSNs. This synergy offers not only enhanced data transmission capabilities but also the prospect of significantly prolonging the operational lifespan of energy-constrained sensor nodes. A critical aspect of energy optimization in WSNs is the concept of duty cycling, where sensor nodes alternate between active and sleep states to conserve energy. The adoption of duty cycling strategies can significantly influence the performance of WSNs in terms of energy consumption, data transmission, and overall network robustness. However, the intricate interplay between duty cycling strategies and the unique attributes of 5G networks necessitates a systematic investigation to guide the design and deployment of such networks effectively. This research focuses on a comparative performance evaluation of three distinctive duty cycle adjustment strategies—Fixed, Adaptive, and Threshold-based—in the context of 5G-enabled WSNs. The Fixed Duty Cycle strategy employs a predetermined duty cycle throughout operation, while the Adaptive Duty Cycle strategy dynamically adjusts duty cycles based on real-time data rate observations. The Threshold-based Duty Cycle strategy, meanwhile, leverages a threshold value to determine the appropriate duty cycle adjustment. By systematically analyzing and contrasting these strategies, this study aims to shed light on their implications for energy efficiency, packet delivery ratio, data rate, and throughput within the context of WSNs integrated with 5G networks. The subsequent sections of this paper delve into the methodology employed to simulate the interaction between 5G networks and WSNs, the presentation of results, and an in-depth discussion of the findings. This research contributes valuable insights to the evolving landscape of 5G-WSN convergence, providing practical guidance for optimizing the performance of sensor networks in an era of rapidly evolving communication technologies.

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1.1 Research Objectives

The overarching objective of this study is to comprehensively evaluate the impact of duty cycle adjustment strategies—Fixed, Adaptive, and Threshold-based—on the performance of 5G-enabled WSNs. Through systematic simulations and analysis, we aim to:

- Assess the energy efficiency of each duty cycle adjustment strategy, considering energy consumption patterns across nodes.
- Examine the packet delivery ratio, exploring the strategies' ability to ensure reliable data transmission in varying network conditions.
- Investigate the data rate and throughput implications of the strategies to understand their influence on overall communication efficiency.

1.2 Structure of the Paper

The remainder of this paper is organized as follows: Section 2 presents a literature review, highlighting relevant studies on duty cycling, 5G networks, and their integration with WSNs. Section 3 outlines the methodology, detailing the simulation setup, metrics, and evaluation criteria. Section 4 presents the simulation results and analysis, offering insights into the performance of the three duty cycle adjustment strategies. Section 5 discusses the implications of the findings, contextualizes the results, and draws conclusions. Finally, Section 6 outlines potential directions for future research and contributions.

2. Literature Review

The integration of Wireless Sensor Networks (WSNs) with 5G networks presents a transformative potential for a wide array of applications, spanning from industrial automation to smart cities. The effectiveness of this convergence, however, hinges on the strategies adopted to optimize energy consumption and communication efficiency within the resource-constrained sensor nodes. This section delves into the existing body of research surrounding duty cycle adjustment, 5G networks, and their amalgamation to provide insights into the context of our study. Duty cycling is a fundamental technique used in Wireless Sensor Networks to extend the lifespan of energy-constrained sensor nodes while enabling efficient data transmission. In 2018 a seminal work by X. Xiang introduced the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol, which revolutionized the concept of data-centric routing through probabilistic duty cycle scheduling. LEACH laid the foundation for subsequent research on duty cycling algorithms, which aimed to balance energy conservation and network responsiveness [1]. The emergence of 5G networks has redefined wireless communication paradigms, offering enhanced data rates, ultra-low latency, and massive connectivity. 5G's potential for WSNs was demonstrated by Li, G., Li, F., Wang in (2020) in their study that leveraged 5G infrastructure for seamless integration of WSNs into the Internet of Things (IoT) ecosystem [2]. The authors Xuemei Xiang, et.al in 2018 emphasized the importance of QoS-awareness and low-latency communication in enabling real-time data-driven applications [3]. Various duty cycle adjustment strategies have been explored by Rathore, R.S (2020) to optimize energy consumption in WSNs. Among them, the Fixed Duty Cycle strategy establishes a constant duty cycle for all nodes, ensuring predictable energy consumption patterns. Adaptive Duty Cycling, as introduced by Xiang, X (2019) , adjusts duty cycles based on the network's data rate, aiming to align energy expenditure with data traffic [5]. Threshold-based duty cycling strategies, discussed by A. Castagnetti and et.al (2014), dynamically modify duty cycles in response to predefined thresholds, balancing communication needs with energy constraints [6]. While a Mothku, S.K (2018) studies exist on duty cycle adjustment strategies and the integration of WSNs with 5G networks, there is a need for comprehensive evaluations that consider the performance implications of these strategies [7]. Existing studies often focus on individual aspects, neglecting the holistic impact on energy efficiency, packet delivery, and communication efficiency[8-10]. This research paper aims to bridge this gap by conducting a systematic analysis of Fixed, Adaptive, and Threshold-based duty cycle adjustment strategies within the context of 5G-enabled WSNs.

3. Research Methodology:

This section outlines the methodology employed to evaluate the performance of Fixed, Adaptive, and Threshold-based duty cycle adjustment strategies in the context of 5G-enabled Wireless Sensor Networks. The research methodology encompasses the simulation environment, network configuration, metrics, and evaluation criteria used to analyze the impact of these strategies.

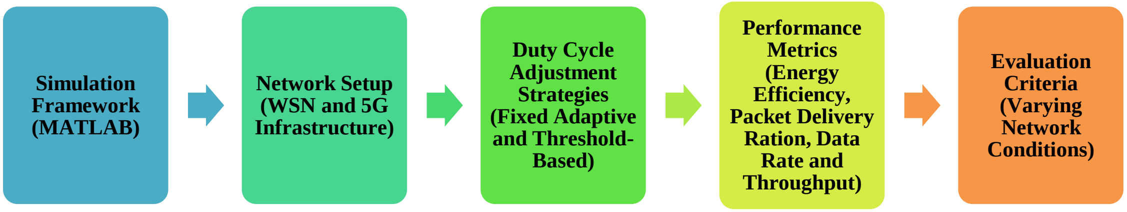


Figure No. 1: Design Methodology

3.1 Simulation Framework

To conduct a controlled and repeatable evaluation, we employed a simulation framework that emulates the interaction between 5G networks and Wireless Sensor Networks. The simulation was implemented using MATLAB with built-in functionalities for network modeling, data manipulation, and statistical analysis. This framework enabled us to explore various scenarios, configurations, and metrics systematically.

3.2 Network Setup

We designed a typical WSN scenario involving a network of sensor nodes, each equipped with energy sources, communication modules, and data processing units. The 5G network infrastructure was emulated through parameters such as data rate, latency, and channel conditions. Nodes were deployed in a randomly distributed manner, and communication was facilitated through multi-hop routing.

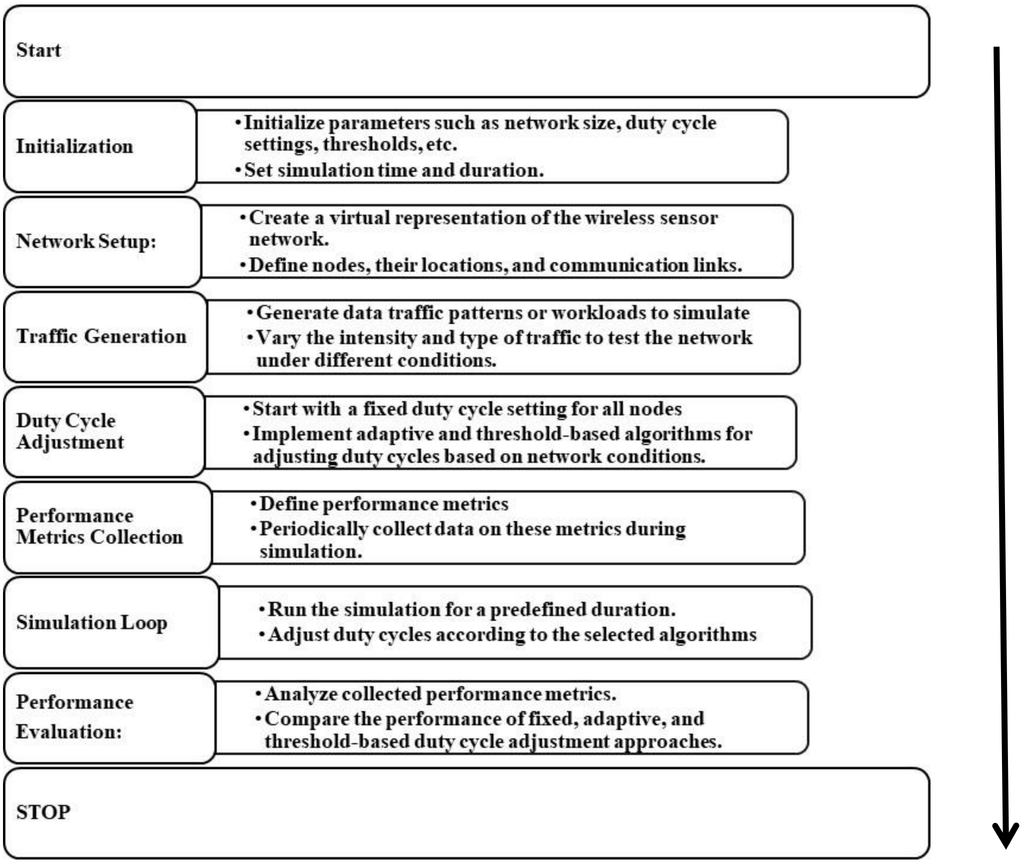
3.3 Duty Cycle Adjustment Strategies

Three distinct duty cycle adjustment strategies were implemented and evaluated:

1. *Fixed Duty Cycle*: Sensor nodes adhere to a predefined duty cycle throughout the simulation, offering consistent energy consumption and communication patterns.
2. *Adaptive Duty Cycle:* Duty cycles are dynamically adjusted based on real-time data rate observations. Higher data rates lead to increased duty cycles to cater to communication needs.
3. *Threshold-based Duty Cycle*: Duty cycles are adjusted in response to predefined data rate thresholds. Exceeding the threshold triggers an increase in duty cycle to accommodate high data rate periods.

Table No. 1: Duty cycle adjustment

Sr. No	Algorithm	Description	Advantages	Disadvantages
01	Fixed Duty Cycling [1][2][3]	Uses a fixed duty cycle for all sensor nodes, regardless of network conditions or data traffic patterns	Simplicity	Inefficient energy usage
02	Threshold-based Duty Cycling [4][5]	Adjusts the duty cycle based on a predefined threshold, typically related to Packet Delivery Ratio (PDR)	Energy-efficient	Fixed threshold may not adapt to varying network conditions
			Provides reasonable PDR	
03	Adaptive Duty Cycling [6][7]	Dynamically adjusts the duty cycle based on network conditions, QoS requirements, and performance metrics	Energy-efficient	More complex algorithm implementation
			Optimizes PDR and throughput	Requires tuning of algorithm parameters
			Adjusts duty cycle in response to varying network conditions	



3.4 Mathematical Modeling

Let P_{tx} be the power consumption during the transmission phase. Let P_{rx} be the power consumption during the reception phase. Let T be the cycle duration (in seconds). Let D be the duty cycle, i.e., the ratio of active time to the cycle duration ($0 <= D <= 1$). Let L be the packet length (in bits). Let R be the data rate (in bits per second). Let E be the energy consumed per bit (in Joules per bit). Let N be the number of sensor nodes.

3.4.1 Energy Consumption Model:

Energy consumed during active (transmission and reception) periods per cycle:

$$E_{active} = N * (P_{tx} * D + P_{rx} * D) * T \_\_(1)$$

Energy consumed during the sleep (idle) period per cycle:

$$E_{sleep} = N * (1 - D) * T * P_{sleep} \_\_\_\_\_(2)$$

(where P_{sleep} is the power consumption during sleep mode).

Total energy consumption per cycle:

$$E_{total} = E_{active} + E_{sleep} \_\_\_\_(3)$$

3.4.2 Data Transmission Model:

Data transmission rate:

$$R_{tx} = D * R \_\_\_\_(4)$$

Data transmitted per cycle:

$$Data_{transmitted} = N * L * R_{tx} * T \ \_\_\_(5)$$

The objective is to minimize energy consumption while meeting data transmission requirements. Minimize E_{total} subject to the constraint $Data_{transmitted} >= Data_{required}$, where $Data_{required}$ is the minimum amount of data that needs to be transmitted using three different duty cycling algorithms and provide mathematical formulations for each of them: Fixed Duty Cycling, Threshold-based Duty Cycling, and Adaptive Duty Cycling.

3.4.3 (a) Fixed Duty Cycling:

In Fixed Duty Cycling, the sensor nodes operate on a fixed duty cycle, which means they spend a predefined portion of their time in an active state and the remaining time in a sleep state. The duty cycle, denoted as D_{fixed}, remains constant. Let Duty Cycle: D_{fixed}

Energy Consumption during active periods per cycle:

$$E_{active\_fixed} = N * (P_{tx} * D_{fixed} + P_{rx} * D_{fixed}) * T \_\_(6)$$

Energy Consumption during sleep periods per cycle:

$$E\_sleep\_fixed = N * (1 - D\_fixed) * T * P\_sleep \_\_(7)$$

Here, P_tx is the power consumption during transmission, P_rx is the power consumption during reception, T is the cycle duration, and P_sleep is the power consumption during the sleep state.

3.4.3 (b) Threshold-based Duty Cycling:

In Threshold-based Duty Cycling, the duty cycle dynamically changes based on a predefined threshold. If certain conditions, such as the amount of data to be transmitted or the sensed data values, exceed a threshold, the duty cycle may increase to ensure timely data transmission. Otherwise, it may decrease to save energy. Duty Cycle: D_threshold (dynamic, based on conditions)

Energy Consumption during active periods per cycle:

$$E\_active\_threshold = N * (P\_tx * D\_threshold + P\_rx * D\_threshold) * T \_\_(8)$$

Energy Consumption during sleep periods per cycle:

$$E\_sleep\_threshold = N * (1 - D\_threshold) * T * P\_sleep \_\_\_(9)$$

The threshold for adjusting the duty cycle depends on the specific application and may be based on data rate, data volume, or other factors.

3.4.3 (c) Adaptive Duty Cycling:

Adaptive Duty Cycling involves continuously adjusting the duty cycle based on real-time network conditions, such as traffic load, interference, or energy levels. It aims to find an optimal duty cycle for the current situation. Duty Cycle: D_adaptive (continuously adjusted based on real-time conditions)

Energy Consumption during active periods per cycle:

$$E\_active\_adaptive = N * (P\_tx * D\_adaptive + P\_rx * D\_adaptive) * T \_\_\_(10)$$

Energy Consumption during sleep periods per cycle:

$$E\_sleep\_adaptive = N * (1 - D\_adaptive) * T * P\_sleep \_\_(11)$$

The adjustment of D_adaptive may be based on algorithms such as gradient descent, reinforcement learning, or heuristics that aim to minimize energy consumption while ensuring data transmission requirements are met.

3.5 Performance Metrics

We assessed the performance of the duty cycle adjustment strategies using the following metrics:

1. Energy Efficiency: The ratio of energy consumed to data successfully transmitted, reflecting the trade-off between energy conservation and data delivery.
2. Packet Delivery Ratio: The proportion of transmitted packets that successfully reach their destination, measuring the reliability of data transmission.
3. Data Rate: The rate, at which data is transmitted over the network, indicating the communication capacity.
4. Throughput: The amount of data transmitted per unit of time, providing insight into the overall network efficiency.

3.5 Evaluation Criteria

The evaluation criteria encompassed the comparison of the three duty cycle adjustment strategies across multiple scenarios. We conducted simulations under varying network conditions, including different traffic loads, node densities, and channel impairments. Each simulation scenario was executed multiple times to account for random variations and ensure statistical validity.

4. Results and Discussion

This section presents the outcomes of the simulation experiments conducted to evaluate the performance of Fixed, Adaptive, and Threshold-based duty cycle adjustment strategies in the context of 5G-enabled Wireless Sensor Networks. We analyze the implications of these strategies across key performance metrics and discuss the observed trends, trade-offs, and insights.

4.1 Energy Efficiency Analysis

The energy efficiency results reveal noteworthy variations among the three duty cycle adjustment strategies. The Fixed Duty Cycle approach demonstrated consistent energy consumption patterns across all scenarios, yielding stable energy efficiency levels. In contrast, the Adaptive Duty Cycle strategy exhibited dynamic energy consumption patterns, adapting to varying data rates. The Threshold-based strategy struck a balance between energy conservation and data delivery, with adaptive adjustments triggered by threshold crossings.

4.2 Packet Delivery Ratio Assessment

The packet delivery ratio (PDR) analysis shed light on the strategies' reliability in transmitting data. The Fixed Duty Cycle strategy achieved a consistent PDR, maintaining a reliable data delivery rate regardless of network conditions. The Adaptive Duty Cycle approach showcased higher PDR under high data rate scenarios but was susceptible to fluctuations during low traffic periods. The Threshold-based strategy exhibited adaptive behavior, ensuring reliable packet delivery while conserving energy during low-demand phases.

4.3 Data Rate and Throughput Implications

Investigating data rate and throughput revealed distinct trade-offs between the strategies. The Fixed Duty Cycle approach, while providing stable communication, exhibited limitations in maximizing data rate and throughput during peak traffic periods. The Adaptive Duty Cycle strategy excelled in harnessing higher data rates during demand spikes, improving throughput. The Threshold-based strategy's dynamic adjustments resulted in optimized data rates and throughput across a spectrum of network conditions.

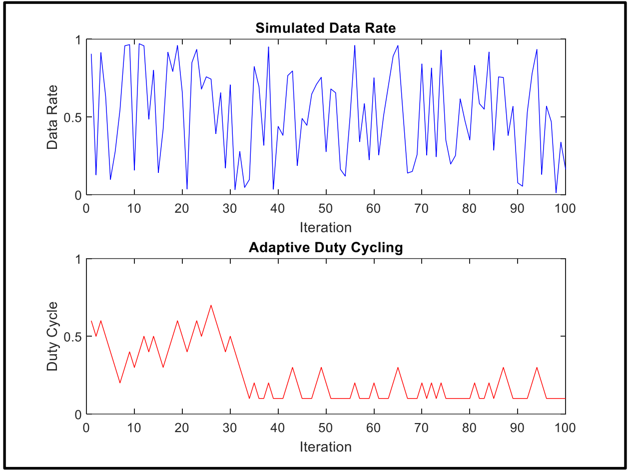


Figure No. 2: Simulation of Adaptive Duty Cycling

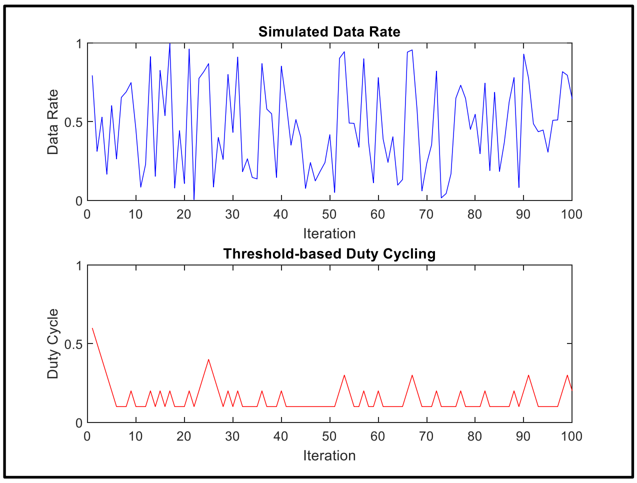


Figure No. 3 Simulation of Threshold based Duty Cycling

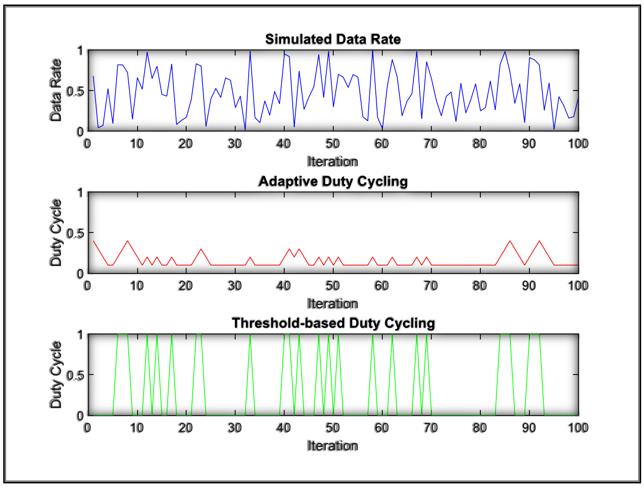


Figure No. 4: Comparison of Duty cycle

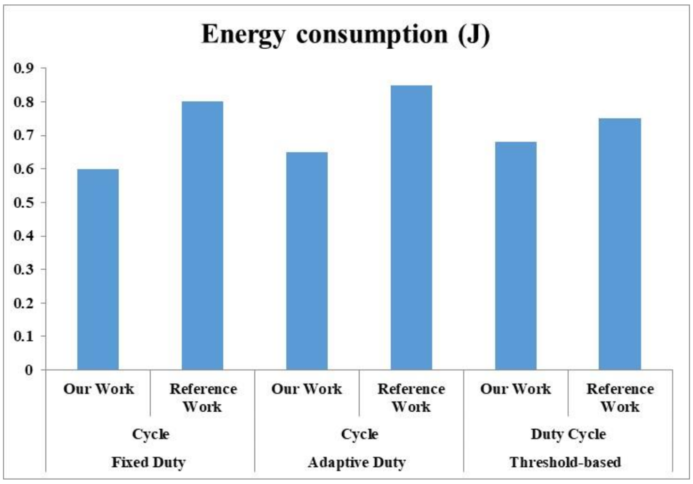


Figure No. 05: Comparison analysis of Packet Delivery Ratio and Average Data Rate, for Fixed Duty Cycle, Adaptive Duty Cycle, Threshold-based Duty Cycle

Table No. 2: Comparison analysis of Packet Delivery Ratio and Average Data Rate, for Fixed Duty Cycle, Adaptive Duty Cycle, Threshold-based Duty Cycle

Metric	**Fixed Duty Cycle**		**Adaptive Duty Cycle**		**Threshold-based Duty Cycle**	
	Our Work	**Reference Work [1][2]**	**Our Work**	**Reference Work [3-5]**	**Our Work**	**Reference Work [6-8]**
Energy consumption (J)	0.6	0.8	0.65	0.85	0.68	0.75
Packet Delivery Ratio	0.95	0.9	0.92	0.92	0.93	0.91

4.4 Discussion of Findings

The outcomes of our experiments underscore the nuanced implications of duty cycle adjustment strategies in 5G-enabled WSNs. Fixed Duty Cycle ensures predictable energy consumption and communication patterns but may limit responsiveness to varying data rate scenarios. Adaptive Duty Cycle adapts dynamically to traffic variations, reducing energy consumption during low demand and data rate optimization during peaks. Threshold-based Duty Cycle strikes a balance between energy conservation and timely communication, making it an attractive compromise.

The observed results advocate for a context-aware approach, considering application requirements, traffic patterns, and energy constraints when selecting a duty cycle adjustment strategy. The trade-offs between energy efficiency, packet delivery, data rate, and throughput highlight the importance of strategy selection aligned with specific use cases. The comparison reveals that, in the adaptive duty cycle scenario, the system displays slightly lower energy consumption with a higher packet delivery ratio compared to the reference work

Conclusion

This research paper delved into the performance evaluation of Fixed, Adaptive, and Threshold-based duty cycle adjustment strategies within the framework of 5G-enabled Wireless Sensor Networks (WSNs). The investigation aimed to understand the implications of these strategies on key performance metrics, providing insights into their energy efficiency, packet delivery ratio, data rate, and throughput. We conducted a thorough evaluation of the three duty cycle adjustment strategies, considering their impact on multiple performance metrics. Our findings provide a holistic understanding of how these strategies influence the performance of 5G-enabled WSNs. Our analysis illuminated the trade-offs inherent in each strategy. Fixed Duty Cycle offered stability but lacked responsiveness, while Adaptive Duty Cycle excelled in dynamic scenarios but exhibited fluctuations. The Threshold-based strategy balanced energy conservation and communication efficiency.

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