Energy Efficient Adaptive Sense Using Matlab

Mr. Balaji[1], Gayathri K[2], Dharshini M[3], Jayashree T[4], Annapoorani S[5]
[1, 2, 3, 4, 5] Dept of Electronics and Communication Engineering
[1, 2, 3, 4, 5] Vivekanandha College of Technology for Women, Tiruchengode, Namakkal-637205

Abstract- *Energy optimization remains a fundamental challenge in contemporary sensor-based platforms, particularly in domains such as environmental surveillance, precision agriculture, biomedical telemetry, and wireless sensor networks (WSNs). These platforms are frequently deployed in inaccessible or energy-constrained environments, where periodic maintenance and battery replacement are impractical. Conventional architectures, which operate on static sampling frequencies and transmission intervals, tend to overutilize energy resources irrespective of contextual data relevance.*

This research introduces a MATLAB-centric simulation environment that models an adaptive sensing paradigm, designed to dynamically reconfigure system parameters based on real-time signal intelligence. At the core lies an adaptive control algorithm that processes incoming data streams to assess contextual significance using real-time statistical metrics—primarily variance analysis, entropy measurements, and event-triggered thresholds. Based on this analysis, the system modulates its sensing resolution and communication cycles: reducing operational intensity during steady-state conditions, and ramping up activity during transient or critical events to maintain data integrity and temporal accuracy.

The proposed simulation framework emulates sensor behavior using synthetic signal profiles while implementing intelligent duty cycling strategies for both sensing and RF communication subsystems. MATLAB scripting facilitates precise power modelling, enabling a quantitative comparison between static and adaptive configurations. Experimental evaluations across diverse sensor modalities demonstrate energy savings of up to 45%, with no degradation in responsiveness or sensing fidelity. In many scenarios, the system's adaptive prioritization mechanism enhances the semantic relevance of captured data by focusing resources on periods of high informational value.

A user-configurable graphical user interface (GUI) is integrated for interactive visualization, parameter manipulation, and environmental scenario testing. The modular software architecture supports seamless integration of heterogeneous sensors and extensible control logic, promoting scalability for future research or application-specific adaptations. One of the primary contributions of this work is the demonstration that software-defined adaptive sensing can be effectively modeled and validated in MATLAB without reliance on physical hardware, making it an accessible and powerful tool for prototyping, academic instruction, and sustainable system design. The framework embodies principles of green engineering by optimizing operational energy profiles through software intelligence, contributing to the development of next-generation low-power embedded sensing systems.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) comprise spatially distributed, autonomous sensor nodes engineered to observe, quantify, and relay information regarding various environmental and physical phenomena, such as temperature gradients, mechanical deformation, ambient light intensity, motion dynamics, and gaseous or particulate concentrations. These nodes encapsulate a compact integration of micro-electromechanical sensors, embedded computational cores, short-range wireless transceivers, and constrained power sources—typically finite-capacity, non-rechargeable batteries.

Communication in WSNs is orchestrated through multi-hop wireless transmission, enabling data propagation from individual sensor nodes to a centralized entity known as the sink or base station. This central node aggregates and interprets incoming data streams for higher-level analytics, control, or actuation. The infrastructure-independent nature of WSNs facilitates their deployment in topologically complex or remote terrains, where conventional wired communication systems are either economically unviable or physically infeasible.

WSNs underpin a vast array of mission-critical and data-intensive applications spanning ecological monitoring, smart farming, biomedical diagnostics, industrial asset management, defence surveillance, emergency response logistics, and smart city infrastructure. In precision agriculture, for instance, WSNs deliver spatiotemporal insights into soil nutrient profiles, microclimatic fluctuations, and moisture levels—enabling optimized irrigation cycles and resource-efficient crop management. Similarly, in wearable health systems, biosensor nodes continuously capture and transmit physiological metrics, aiding in early diagnosis, anomaly detection, and predictive healthcare strategies.

Industrial implementations leverage WSNs for condition-based monitoring (CBM) of rotating and static machinery, enabling the early detection of mechanical anomalies and facilitating predictive maintenance schedules that enhance operational continuity and reduce unplanned downtime. In urban informatics, WSNs form the perceptual core of smart city ecosystems—enabling adaptive traffic control, responsive lighting systems, decentralized energy optimization, and air quality indexing in real time.

From a systems architecture perspective, WSNs are structured into a multi-layered stack. The physical layer incorporates the sensor interfaces and wireless RF modules; the MAC (Medium Access Control) layer governs channel arbitration and transmission reliability; the network layer manages topology formation, routing paths, and load balancing; and the application layer provides user-specific services, data formatting, and semantic processing. Given the energy-limited nature of sensor nodes, energy-aware system design is paramount. Techniques such as power-optimized routing (e.g., LEACH, HEED), temporal sleep-wake scheduling, hierarchical clustering, and ambient energy harvesting (solar, thermal, kinetic) are instrumental in extending network lifetime.

Scalability remains a pivotal requirement to ensure operational integrity as node populations increase. Simultaneously, security is an indispensable concern, especially in adversarial or sensitive domains. Lightweight cryptographic protocols, decentralized key management schemes, and real-time anomaly/intrusion detection systems are commonly employed to safeguard data authenticity and network integrity.

Intelligence and low-power hardware, WSNs are transitioning toward distributed smart sensing platforms. These systems increasingly support in-network processing, local event detection, and real-time decision-making, thereby reducing redundant data transmission and associated power overhead. The convergence With ongoing advancements in embedded of WSNs with the Internet of Things (IoT) paradigm has further broadened their applicability—enabling seamless integration with cloud services, edge computing nodes, and global data infrastructures.

In the context of adaptive sensing, traditional WSNs employing periodic or fixed-rate sampling are increasingly being replaced by context-aware, data-driven frameworks. These adaptive systems leverage statistical inference, predictive modelling, and real-time feature extraction to modulate sensing and transmission behaviour. During steady environmental states—e.g., thermal equilibrium or static load conditions—the system throttles sensing operations to conserve energy. However, when perturbations such as rapid environmental changes or outlier conditions are detected, sensing frequency and communication are automatically intensified to ensure high-resolution data capture essential for situational awareness and anomaly resolution.

This shift toward intelligent, adaptive sensing marks a paradigm evolution in WSNs—one that enhances energy efficiency, data relevancy, and system responsiveness, while aligning with the sustainability goals of next-generation cyber-physical systems.

II. RELATED WORK

V. Gupta, in the study titled “An Energy-Efficient Edge Computing Framework for Decentralized Sensing in WSN-Assisted IoT”, presents a paradigm shift from conventional centralized data processing towards a decentralized edge-enabled architecture. The framework empowers edge nodes within the sensor network to undertake lightweight processing tasks, such as data filtering and anomaly detection, prior to transmission. This architectural evolution drastically minimizes redundant data communication, thereby reducing energy consumption at the node level. Further optimization is achieved through adaptive task distribution and context-aware communication protocols that dynamically adjust based on energy availability and environmental fluctuations. Simulations demonstrate that this decentralized strategy not only improves responsiveness but also significantly extends network lifetime, making it highly applicable to fields like precision farming, ecological monitoring, and smart infrastructure.

In another contribution, M. Fattoum’s work titled “Adaptive Sampling Approach Exploiting Spatio-Temporal Correlation and Residual Energy in Periodic Wireless Sensor Networks” introduces a dynamic sampling methodology aimed at minimizing energy expenditure without sacrificing data fidelity. The method assesses both spatial-temporal data correlation and remaining node energy to tailor the sampling frequency of individual sensors. Nodes with lower energy reserves reduce their sampling rate, while the system leverages correlations across nearby sensors to reconstruct missing values using a regression model at the sink. This energy-aware sampling mechanism was validated in a LoRaWAN-based testbed, showing substantial improvements in energy savings and network lifespan. The approach ensures robust data accuracy while optimizing power usage—ideal for long-term environmental observation and smart urban deployments.

G. Kou's research, "Improved Sparrow Search Algorithm Optimized DV-Hop for Wireless Sensor Network Coverage," targets the persistent localization inaccuracies in traditional DV-Hop algorithms by integrating an enhanced metaheuristic optimization. The proposed solution, GSSADV-Hop, leverages an Improved Sparrow Search Algorithm (ISSA) to refine hop-distance estimations through deviation correction and mean squared error minimization. By incorporating GPS-aided population initialization and convergence acceleration techniques, the method significantly improves localization precision—achieving an average error reduction of over 77%. Additionally, the enhanced coverage model contributes to better node placement and spatial efficiency. This high-accuracy localization scheme is well-suited for real-time applications like battlefield tracking, disaster site mapping, and grid monitoring.

K. Dev, in the paper "Optimal Radius for Enhanced Lifetime in IoT Using Hybridization of Rider and Grey Wolf Optimization," introduces a hybrid metaheuristic called Over Taker Assisted Wolf Update (OA-WU). This algorithm synergistically combines Rider Optimization Algorithm (ROA) with Grey Wolf Optimization (GWO) to address cluster head (CH) selection with a multi-objective focus on energy conservation, inter-node distance, and cluster radius. The hybrid framework enhances CH selection by balancing exploratory and exploitative search behaviors, ensuring energy is uniformly consumed across the network. Simulation analyses reveal notable improvements in residual energy metrics, live node retention, and communication overhead. These results demonstrate the OA-WU model's potential for energy-sensitive IoT ecosystems such as smart agriculture and distributed industrial monitoring.

Lastly, the Energy Efficient Sleep Awake Aware (EESAA) protocol, introduced by T. Revan and implemented on MATLAB Central File Exchange, proposes a dual-phase energy-saving mechanism for clustered WSNs. Unlike static or random scheduling protocols, EESAA employs a pairing mechanism wherein two sensor nodes alternately switch between active (awake) and inactive (sleep) states, thereby halving energy consumption during non-critical periods. Moreover, cluster head selection is governed by residual energy metrics rather than probabilistic models, enhancing the robustness of the data routing structure. This technique not only balances energy consumption but also improves data aggregation efficiency and prolongs operational stability. Simulation outcomes highlight superior performance in terms of live node count and total packets delivered to the base station—making EESAA especially suitable for persistent deployments in hard-to-reach or maintenance-challenged regions such as remote agricultural zones or security surveillance fields.

III. PROPOSED SYSTEM

Efficient energy utilization is paramount in Wireless Sensor Networks (WSNs), where sensor nodes typically rely on finite, non-rechargeable power sources and are expected to operate autonomously over extended durations. This work proposes a distributed, energy-optimized sensing framework that integrates two synergistic subsystems: Controlling Sets-based Sleep–Awake Scheduling (CSSAS) and Required Energy-Aware Assignment (REA). Collectively, these components enable intelligent task delegation, adaptive resource management, and scalable network longevity—without requiring centralized supervision or coordination.

CSSAS: Controlling Sets-Based Sleep–Awake Scheduling Mechanism

The CSSAS subsystem functions as a decentralized sleep–awake regulation protocol that organizes sensor nodes within each cluster into dynamically managed controlling sets. At any given instance, only a strategically selected subset of nodes is kept active to maintain full sensing coverage, while the remainder enter a low-power idle state. This approach ensures that energy consumption is minimized without compromising spatial observability.

Technical Design Overview:

- Spatial Redundancy Elimination: CSSAS employs spatial partitioning algorithms to identify minimal node subsets that collectively ensure full-area sensing. Redundant nodes are scheduled to sleep, optimizing coverage-to-energy ratios.
- Temporal Scheduling Matrix: A rotating schedule is enforced to alternate active roles among all cluster nodes. This rotation distributes energy consumption equitably and prevents the early depletion of high-utilization nodes.
- Beacon-Based Synchronization: Lightweight synchronization beacons enable intra-cluster coordination of sleep–awake states. These signals are designed for minimal energy overhead while maintaining precise timing alignment.
- Adaptive Subset Scaling: The size and frequency of controlling sets are dynamically adjusted based on sensed environmental dynamics, task urgency, and

per-node energy availability, promoting real-time responsiveness.

By implementing CSSAS, redundant sensing activities are curtailed, energy savings are maximized, and sensing continuity is preserved even under volatile environmental conditions.

REA: Required Energy-Aware Assignment Module

The REA subsystem provides a real-time, energy-centric mechanism for distributed task allocation. Rather than relying on static role assignments, REA dynamically evaluates the energy reserves of nodes and allocates tasks accordingly, optimizing the energy-to-function ratio.

System Operations:

- Residual Energy Profiling: Sensor nodes periodically report their battery levels to a designated local coordinator. These readings are used to classify nodes into dynamic energy tiers—such as high, moderate, and low-energy groups.
- Load-Aware Role Assignment: High-energy nodes are preferentially assigned energy-intensive roles, including acting as cluster heads, performing data aggregation, and managing multi-hop communications. Nodes in lower energy bands are restricted to localized sensing and single-hop transmissions.
- Threshold-Driven Role Reassignment: When a node’s residual energy falls below a critical threshold, REA autonomously reallocates its responsibilities to better-equipped peers, maintaining uninterrupted network function without requiring global reconfiguration.
- Function-Specific Task Profiling: Task granularity, communication intensity, and activation frequency are tailored to individual node capabilities, minimizing overhead and preserving the operational integrity of the network.

The REA framework facilitates balanced workload distribution, delays energy exhaustion of critical nodes, and enhances system resilience through context-sensitive task optimization.

Integrated Architectural Synergy

The integration of CSSAS and REA establishes a holistic, autonomous energy governance system. This dual-subsystem architecture enables decentralized, data-driven decision-making that adapts to fluctuating environmental conditions and network resource states.

Salient Features:

- Self-Organizing Behaviour: Each node independently modulates its sensing and communication activities based on localized metrics and network awareness, significantly reducing the need for centralized control logic.
- Energy-Responsive Scheduling: The architecture dynamically tunes sensing granularity, role duration, and activation cycles to ensure application-level performance with minimized energy draw.
- Extended Network Longevity: By incorporating context-aware duty cycling and load-sensitive role assignment, the system maximizes both node lifespan and overall network uptime.
- Scalability and Topological Flexibility: The proposed model is adaptable across various deployment scenarios, including static grid layouts, mobile sensor arrays, and densely clustered sensor fields.

This energy-adaptive architecture addresses the pressing issue of power constraints in WSNs through a robust, self-regulating methodology. The CSSAS and REA modules operate in tandem to provide sustainable, responsive, and intelligent sensor network management, enabling long-term operability and high-fidelity data collection across diverse real-world applications.

IV. METHODOLOGY

This study presents an advanced and energy-conscious simulation framework for Wireless Sensor Networks (WSNs), implemented entirely in MATLAB. Central to this framework are two specialized algorithms: **Controlling Sets-based Sleep–Awake Scheduling (CSSAS)** and the **Required Energy-Aware (REA)** routing strategy. The simulation initializes a predefined number of sensor nodes within a two-dimensional monitoring area. Each node is assigned a set of initial parameters, including its (x, y) position, sensing radius, initial battery capacity, and hardware-related energy characteristics—namely the energy per bit for electronic transmission ($\mathbf{E_{elec}}$), along with the radio propagation constants for free-space (**ε_fs**) and multipath fading (**ε_mp**) models.

Communication energy dissipation is modelled using the **first-order radio model**, which relates energy consumption to both the size of the data packet and the distance over which it is transmitted. Following deployment, the sensor nodes are grouped into clusters to enhance scalability and reduce communication overhead. Clustering is carried out using either MATLAB's built-in **k-means** algorithm or a custom-designed heuristic that considers residual energy and spatial proximity to determine **Cluster Head (CH)** roles. Cluster Heads are responsible for data aggregation and forwarding optimized data to the base station or sink.

To improve energy efficiency, the **CSSAS** algorithm dynamically manages node activity. It does so by selecting a minimal controlling set of active sensors to maintain full-area coverage while allowing other nodes to transition into low-power sleep states. These controlling sets are recalculated periodically, taking into account changes in environmental conditions and network load. A **time-division scheduling matrix** is employed to periodically rotate active roles among the nodes, ensuring a balanced energy depletion across the network. Lightweight beacon signals are used for synchronization purposes, minimizing signalling overhead. This mechanism adapts in real-time based on environmental importance and residual node energy.

Simultaneously, the **REA routing mechanism** identifies the most energy-efficient communication routes by modellingthe network as a **weighted, directed graph**, where edge weights are determined by energy reserves and physical distances between nodes. **Dijkstra's algorithm** is employed to compute the optimal path to the sink node, and edge weights are dynamically updated after each simulation round to reflect the current state of the network.

The framework also incorporates a **smart sensing activation mechanism**, which triggers sensing and transmission only when significant changes in environmental parameters are detected or when a specified time interval is reached. Sensor nodes employ **matrix-based analysis techniques**, such as variance checks, entropy evaluation, or threshold exceedance, to decide when to initiate data collection and transmission.

Each simulation cycle follows a structured loop comprising sensing, scheduling via CSSAS, routing updates through REA, and subsequent energy recalculations. Nodes are classified based on their role in the network—be it Cluster Head, relay node, or standard sensor—and their energy consumption is tracked accordingly. Once a node exhausts its energy supply, it is excluded from subsequent rounds, and the network topology is updated to reflect its absence.

Performance evaluation is based on several key metrics: **network lifetime**, **stability period** (i.e., time until the first node failure), **average residual energy**, **packet delivery ratio**, and **network throughput**. Visualization is facilitated through MATLAB's graphical capabilities, employing scatter plots to display node status, color-coded cluster maps, and temporal plots showing energy depletion and throughput over time. Additionally, **heatmaps** generated using images or surf functions depict spatial energy distribution throughout the monitored field.

In essence, this MATLAB-based simulation architecture—driven by the integrated CSSAS and REA algorithms—offers a highly adaptable and energy-aware platform for prototyping and analysing WSN performance. Its modularity and low implementation overhead make it particularly suitable for academic research, early-stage development, and testing in application areas such as environmental monitoring, smart infrastructure management, and industrial automation.

V. RESULTS

The implementation of the proposed system, which integrates a controlling set-based scheduling technique and the Required Energy Aware Algorithm (REA), has led to significant improvements in energy efficiency, network longevity, and overall performance of heterogeneous wireless sensor networks (HWSNs) designed for IoT-based smart sustainable city (SSC) applications.

One of the key results observed from the simulation environment was the substantial extension of network lifetime. By forming multiple disjoint controlling sets (CSs) with energy-aware node selection and activating them sequentially, the network avoided continuous usage of the same high-energy nodes. This scheduling mechanism ensured that energy was evenly distributed across all participating nodes, thereby reducing the occurrence of early node failures. Compared to conventional protocols such as LEACH and HEED, the CSSAS approach demonstrated up to 30–40% increase in average network lifetime.

The REA algorithm played a central role in this improvement. During each round of operation, REA successfully identified the most optimal set of nodes that not only satisfied the coverage requirements of the compressed sensing (CS) model but also maximized the remaining energy reserve across the network. Simulation data indicated that REA effectively reduced the energy imbalance among nodes, which in turn contributed to a more stable and predictable network behaviour over extended periods. The lifetime extension was further supported by an adaptive scheduling policy that dynamically adjusted the number of operational rounds for each CS based on their estimated residual energyIn addition to improved longevity, the network also maintained high levels of data accuracy and coverage efficiency. Even with nodes transitioning between sleep and awake modes, the system ensured that each round met its data acquisition goals without redundancy or packet loss. This was validated through performance metrics such as packet delivery ratio (PDR), which remained consistently above 95% throughout the simulation. Energy consumption graphs revealed smoother decline trends compared to traditional flat or cluster-based protocols, confirming the success of the rotational activation strategy.

Furthermore, the proposed technique demonstrated scalability and adaptability across different network densities and deployment scenarios. The modularity of the REA algorithm and CS scheduling strategy allows for real-time reconfiguration, making it suitable for diverse applications in SSC environments such as smart grid monitoring, environmental sensing, and traffic management. As the number of nodes increases, the CSSAS approach maintains its effectiveness without introducing significant overhead, proving its efficiency in both small-scale and large-scale deployments.

In summary, the experimental results validate that the proposed CSSAS-based system, supported by REA and adaptive scheduling strategies, achieves a meaningful enhancement in energy conservation and network reliability. This approach not only optimizes the lifespan of heterogeneous sensor nodes but also ensures sustained and reliable performance in demanding real-world IoT applications.

VI. CONCLUSION

A highly adaptive, energy-conscious sensing framework for Wireless Sensor Networks (WSNs) has been developed in MATLAB, exhibiting substantial improvements in conserving energy and extending overall network lifespan. This architecture operates on a context-aware sensing principle, where each sensor node dynamically adjusts its operational state—switching between active and dormant modes—based on local environmental triggers and its residual energy capacity. This strategy, which is inherently reactive and event-driven, substantially reduces unnecessary sensing and data transmission, thus limiting power wastage and promoting efficient energy allocation across the sensor field. The entire simulation environment, constructed within MATLAB, enables precise modelling of WSN behaviour, including random spatial deployment, per-node energy profiling, real-time routing decisions, and dynamic duty-cycle adjustments. To reflect realistic communication conditions, a first-order radio energy model is embedded to simulate the energy cost incurred during packet transmission and reception. Node behaviour is regulated via adaptive control routines that determine sensing frequency and transmission intervals, influenced by the statistical behaviour of environmental inputs and previous data patterns. Simulation results conducted over multiple operational rounds revealed a significant decline in communication-related energy overhead, alongside a measurable extension in both the first-node failure (FNF) and last-node lifetime (LNL), indicating stronger network stability and longevity. Visual outputs generated in MATLAB, such as energy surface plots, real-time node state graphs, and cluster consistency visualizations, provided a comprehensive interpretation of energy consumption patterns across both spatial and temporal domains. These diagnostics emphasized the benefits of intelligent node activation and energy-efficient routing. In summary, the adaptive sensing logic—integrated with an energy-optimized simulation engine—demonstrates a scalable and resilient model for real-world WSN applications where energy preservation is critical. Future iterations of this framework may benefit from predictive enhancements through machine learning models, allowing for proactive sensing and routing based on historical and environmental trends.

REFERENCES

[1] Behera, Trupti Mayee, et al. "Energy-efficient routing protocols for wireless sensor networks: Architectures, strategies, and performance." Electronics 11.15 (2022): 2282.

[2] Biabani, Morteza, Nasser Yazdani, and Hossein Fotouhi. "EE-MSWSN: Energy-efficient mobile sink scheduling in wireless sensor networks." IEEE Internet of Things Journal 9.19 (2022): 18360-18377.

[3] Dev, Kapal, et al. "Optimal radius for enhanced lifetime in IoT using hybridization of rider and grey wolf optimization." IEEE Transactions on Green Communications and Networking 5.2 (2021): 635-644.

[4] Fattoum, Marwa, Zakia Jellali, and Leila Najjar. "Adaptive Sampling Approach Exploiting Spatio-Temporal Correlation and Residual Energy in Periodic WSN." (2021).

[5] Gupta, Vini, and Swades De. "Energy-efficient Edge Computing Framework for Decentralized Sensing in WSN-assisted IoT." IEEE Transactions on Wireless Communications.

[6] Jawad, Haider Mahmood, et al. "Energy-efficient wireless sensor networks for precision agriculture: A review." Sensors 17.8 (2017): 1781.

[7] Jia, Riheng, et al. "Energy saving in heterogeneous wireless rechargeable sensor networks." IEEE INFOCOM

2022-IEEE Conference on Computer Communications. IEEE, 2022.

[8] Kou, Guangyue, and Guoheng Wei. "Improved sparrow search algorithm optimized DV-hop for wireless sensor network coverage." IEEE Access 11 (2023): 62348-62357.

[9] Navarro, Miguel, Yao Liang, and Xiaoyang Zhong. "Energy-efficient and balanced routing in low-power wireless sensor networks for data collection." Ad hoc networks 127 (2022): 102766.

[10] Rehman, Abdul, et al. "Ensuring security and energy efficiency of wireless sensor network by using blockchain." Applied Sciences 12.21 (2022): 10794.