International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 1s
***Article Received:** 28 November 2022 **Revised**: 27 December 2022 **Accepted**: 02 January 2023 **Published**: 10 January 2023*

Wireless Sensor Networks: A Comprehensive Review of Architecture, Energy Optimization, and Tactical Challenges

[1]Prof. Jainam S Shah, [2]Prof. Krunal H Parmar, [3]Prof. Pinal D Salot
[1]*Biomedical Engineering Departmemt*
Government Polytechnic, Ahmedabad, India
shahjainamic@yahoo.com

[2]*Biomedical Engineering Department*
A.V.Parekh Technical Institute
Rajkot, India
krunal.parmar03@gmail.com

[3]*Computer Engineering Department*
L.D. College of Engineering, Ahmedabad, India
pinal.salot@gmail.com

Abstract— Wireless Sensor Networks (WSNs) have emerged as a foundational technology for the realization of the Internet of Things (IoT), facilitating autonomous monitoring across industrial, medical, and environmental landscapes. Despite their proliferation, the operational longevity of WSNs is acutely bottlenecked by the finite energy reserves of individual sensor nodes. This paper provides a systematic, multi-dimensional review of WSN architectures, protocol stacks, and energy conservation paradigms. We synthesize literature spanning 2014–2022 to critically analyze the trade-offs between network throughput and power consumption. The review distinguishes itself by providing a granular comparison of hardware operational components and a robust performance mapping of routing protocols (LEACH, PEGASIS, TEEN). Our findings highlight a significant research shift from basic connectivity toward intelligent, self-sustaining networks. The paper concludes with an extensive roadmap of 20 future research directions to guide scholars toward unresolved challenges in energy harvesting and AI-driven network management.

***Keywords*—**Wireless Sensor Networks, Energy Conservation, Network Lifetime, Sensor Node

1. Introduction

In recent years, Wireless Sensor Networks (WSNs) have attracted considerable global research attention due to their ability to enable large-scale, autonomous monitoring of physical and environmental phenomena [24]. WSNs represent a key distributed computing paradigm that supports a wide spectrum of applications, including industrial process automation, healthcare monitoring, military surveillance, structural health assessment, and environmental observation [1], [2]. A WSN can be defined as a distributed system composed of a large number of spatially dispersed, low-cost sensor nodes that collaboratively sense, process, and transmit data from a monitored region to a centralized sink node or base station for further analysis.

Each sensor node typically performs three core functions: sensing, computation, and wireless communication. The sensed data are forwarded either directly or through multi-hop communication paths to a sink node, which may process the information locally or relay it to external networks such as the Internet or cloud-based platforms [3]. Due to their compact physical dimensions, sensor nodes are inherently constrained in terms of processing capability, memory capacity, communication bandwidth, and, most critically, energy availability [26]. A typical sensor node integrates a sensing unit, a radio transceiver, an embedded processing and storage unit, and a power unit powered by a small-capacity battery.

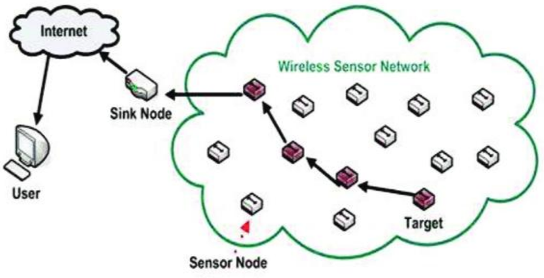

Fig. 1. A typical structure of Wireless Sensor Networks

Depending on application requirements, sensor nodes may be equipped with one or more sensing modalities, enabling the observation of physical phenomena across infrared, acoustic, optical, seismic, magnetic, radio, biological, and chemical domains [4]. Figure 1 illustrates a representative architecture of a wireless sensor network, highlighting the interaction between distributed sensor nodes and the sink. Due to advancement in Micro-Electro-Mechanical Systems (MEMS) technology, sensors are becoming smaller in size, low cost & low power operated [1].

2. Deployment Models of Wireless Sensor Networks

The deployment strategy of sensor nodes plays a crucial role in determining network performance, coverage, and energy efficiency[13]. In general, WSN deployments can be categorized as deterministic or random. In deterministic deployment, sensor nodes are placed at predefined locations, which is common in industrial monitoring and structural health applications where precise coverage is required [2]. In contrast, random deployment is typically employed in hostile or inaccessible environments, such as battlefield surveillance or disaster monitoring, where sensor nodes are dispersed using aerial or mechanical means [6].

Furthermore, WSNs can be deployed in flat or hierarchical topologies. In flat architectures, all sensor nodes perform identical roles and communicate directly or via multi-hop routing to the sink. [4] Although simple to implement, flat architectures often suffer from poor scalability and uneven energy dissipation.[2],[25],[32] Hierarchical or clustered architectures address these limitations by organizing nodes into clusters, where cluster heads aggregate data from member nodes before transmitting it to the sink, thereby reducing communication overhead and improving network lifetime [7],[34].

3. Communication Paradigms in WSNs

Communication in WSNs is predominantly data-centric rather than address-centric, reflecting the application-driven nature of sensed information. Common communication paradigms include single-hop and multi-hop transmission. In single-hop communication, sensor nodes transmit data directly to the sink, which is feasible only for small-scale networks due to excessive energy consumption over long distances. Multi-hop communication, in contrast, allows nodes to forward data through intermediate nodes, significantly reducing transmission power requirements and improving scalability [8].

Additionally, WSN communication paradigms can be classified as time-driven, event-driven, or query-driven. Time-driven networks periodically transmit sensed data, making them suitable for continuous monitoring applications. Event-driven networks transmit data only when specific thresholds are exceeded, which is advantageous for energy conservation in time-critical scenarios. Query-driven networks respond to explicit requests from the sink, offering flexibility in data acquisition [9].

Wireless sensor network technology offers several advantages over conventional networking approaches, including low deployment cost, scalability, flexibility, fault tolerance, and ease of installation, which collectively support its applicability in diverse operational environments [31],[33]. Moreover, advances in Micro-Electro-Mechanical Systems (MEMS) technology have enabled the development of increasingly compact, low-cost, and energy-efficient sensor nodes, thereby accelerating the adoption and practical deployment of WSNs in large-scale Internet of Things (IoT) ecosystems [10],[11].

A. *Structure of Wireless Sensor Node*

A Sensor node is made up of four basic components such as sensing unit, processing unit, transceiver unit and power unit as shown in Fig.2. It has also application dependent additional components such as a location finding system, a power generator and a mobilizer. Sensing units are usually composed of two subunits: sensors and analog to digital converters (ADCs)[14]. The analog signals produced by the sensors are converted to digital signals by ADC and then fed into processing unit. The processing unit

International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 1s
***Article Received:** 28 November 2022 **Revised**: 27 December 2022 **Accepted**: 02 January 2023 **Published**: 10 January 2023*

comprises of processor and storage unit. It is responsible for managing the task of sensor nodes. A transceiver unit is used to transmit sensor data to network or we can say it connects sensor node to network. One of the most important components of sensor node is power unit.

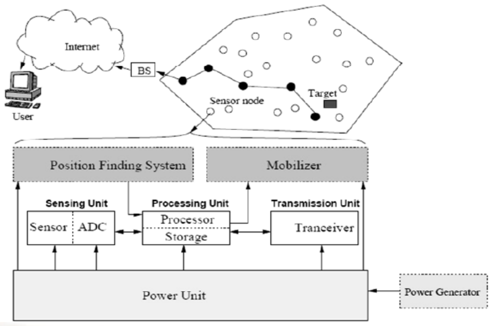

Fig. 1 The components of a sensor node

Component	Function	Power Consumption	Technical Detail	Pros	Cons
Transceiver	Comms	65% – 85%	Idle/RX/TX states	Critical for network	Massive power leak
Micro-controller	Task Mgmt	10% – 15%	Manages sleep cycles	Low power standby	Limited memory
Sensing Unit	Data Acq	5% – 10%	Variable by sensor	High fidelity	ADC drain

Table 1 Comparison of Operational Components & Energy Impact

B. *Communication Structure of Wireless Sensor Networks*

The sensor nodes are usually distributed in area for monitoring environment conditions as well as to measure different physical parameters like temperature, humidity etc. Each sensor node has the capability to collect data and to effectively communicate it to sink node or end user. Data are routed back to end user by a multi-hop infrastructure-less architecture through the sink as shown in Fig 1.

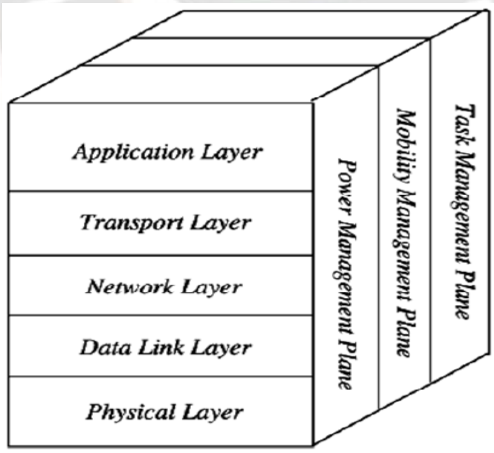

Fig. 2 Wireless Sensor Network Protocol Stack

The protocol stack used by sink node and sensor node is shown in Fig 3. This protocol stack combines power and routing awareness, integrates data with networking protocols, communicates power efficiently through wireless medium and promotes cooperative efforts of sensor nodes. The protocol consists of application layer, transport layer, network layer, data link layer, physical layer, power management plane, mobility management plane, and task management plane [21]. **Physical Layer:** Frequency selection and modulation. **Data Link Layer:** Minimizing collisions and "Idle Listening."**Network Layer:** Multi-hop routing to minimize power loss [37].**Transport Layer:** Lightweight data flow management. Application Layer: Software and user interface.

4. Cross-Layer Energy Implications

Traditional WSN design adheres to strict layer separation, where each protocol layer (Physical, MAC, Network) independently performs its tasks. However, this siloed approach often leads to suboptimal energy use due to hidden interactions between layers [8],[16]. Cross-layer design breaks this isolation by enabling information sharing and joint optimization across layers to improve energy efficiency [2], [8],[30],[37].

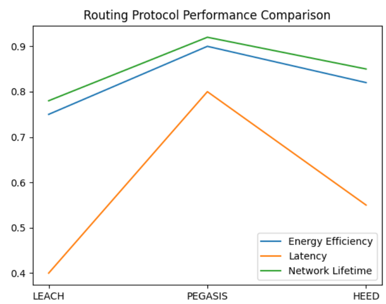

Fig. 3. shows the proposed cross-layer energy-aware architecture that integrates PHY, MAC, and Network layer optimizations [5].

For example: PHY layer **transmission power** settings can be adjusted based on MAC layer collision or congestion feedback to reduce retransmissions and energy waste [15],[19],[26].

MAC layer **duty-cycling** schedules can be adapted using network layer queue lengths, reducing idle listening overhead and overall energy consumption [17].

Network layer routing decisions can incorporate node residual energy and link quality metrics from lower layers to prolong network lifetime [18].

Analytically, let E_{TX} *(r, b)* and E_{RX} *(b)*$E_{TX}\ (r, b)$ denote the energy for transmitting and receiving (b) bits over distance (d), respectively. Traditional layered energy cost is:

$$E_{total} = \sum_{i=1}^{N} (E_{TX}^{(i)} + E_{RX}^{(i)}).$$

where inter-layer interactions are not considered. Cross-layer optimization introduces coupling terms that reduce redundant energy usage, often modelled as:

$$E_{CL} = E_{total} - \Delta E,$$

Where (ΔE) represents energy savings achieved by eliminating protocol overheads and reducing collisions through joint parameter adaptation [8].

Cross-layer strategies have been shown to reduce communication energy significantly compared to layered designs by minimizing overheads, retransmissions, and idle listening.

5. Integrated System Model with Cross-Layer Extensions

When extended to include cross-layer feedback, the energy cost for a given node can be expressed as:

$$E_{\text{node}} = E_{TX} + E_{RX} + E_{\text{overhead}},]$$

where $E_{\text{overhead}},$ includes retransmissions due to MAC collisions, routing control messages, and wake/sleep switching costs. Cross-layer optimization aims to reduce $E_{overhead}$ by collaborative parameter tuning across layers:

$$[E_{\text{overhead}} = f(\text{MAC} * sched, \text{PHY} * pwr, \text{Net}_{route}),]$$

Where (MAC * *sched*, PHY * *pwr*, Net $_{route}$) represent the tunable parameters at their respective layers. A well-designed cross-layer function (f(.)) can minimize total energy while satisfying connectivity and QoS requirements. $([IJERT][1])$

6. System Model and Analytical Framework

This section presents the analytical system model adopted to evaluate energy consumption in Wireless Sensor Networks (WSNs). The model is based on the widely accepted first-order radio energy dissipation framework and is extended to incorporate cross-layer energy interactions between the physical, MAC, and network layers.

A. Network Assumptions and System Overview

Consider a WSN consisting of (N) homogeneous sensor nodes randomly deployed over a two-dimensional monitoring area. Each node is equipped with sensing, processing, and wireless communication capabilities and operates on a limited energy supply. A single sink node with comparatively higher computational and energy resources is assumed to be located either inside or at the boundary of the sensing field.

Data communication between sensor nodes and the sink follows a multi-hop paradigm to minimize long-distance transmissions. Each node periodically generates fixed-length data packets and forwards them either directly or via intermediate nodes depending on the routing strategy employed. Similar assumptions are widely adopted in analytical studies of energy-aware routing and clustering protocols in WSNs [4], [8], [30].

B. First-Order Radio Energy Model

To analytically quantify communication energy consumption, the first-order radio model is employed, which has been extensively used in evaluating routing and clustering protocols such as LEACH, PEGASIS, and HEED [30], [4],[35].

Let: (L): denote the packet length in bits,

(d): distance between transmitter and receiver

E_{elec} : denote the energy consumed by the transmitter or receiver circuitry per bit,

ϵ_{fs}, ϵ_{mp} denote the amplifier energy factors for free-space and multipath propagation models, respectively.

The energy required to transmit an (L)-bit packet over a distance (d) is given by:

$$E_{TX}(L,d) = \begin{cases} L \cdot E_{elec} + L \cdot \epsilon_{fs} \cdot d^2, & d < d_0 \\ L \cdot E_{elec} + L \cdot \epsilon_{mp} \cdot d^4, & d \geq d_0 \end{cases}$$

where the threshold distance (d_0) is defined as:

$$[d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}}]$$

The energy required to receive an (L)-bit packet is expressed as:

$$[E_{RX}(L) = L \cdot E_{elec}]$$

Equations (1)–(3) clearly indicate that communication energy increases rapidly with distance, justifying the adoption of multi-hop routing and clustering mechanisms in large-scale WSN deployments [4], [30],[37].

Protocol	Category	Energy Efficiency	Scalability	Latency	Complexity
LEACH	Hierarchical	High	Moderate	Low	Low
PEGASIS	Chain-based	Very High	Low	High	Moderate
TEEN	Reactive	High	Moderate	Moderate	High
Direct	Flat	Very Low	Very Low	Minimum	Minimum

Table 2 Analytical Mapping of Protocol Performance

C. Cross-Layer Energy Consumption Model

Traditional layered network design treats each protocol layer independently, often leading to redundant operations and excessive energy expenditure. In contrast, cross-layer optimization enables coordinated decision-making across layers to minimize overall energy consumption [8].

The total energy consumption of a sensor node over a given operational period can be expressed as:

$$[E_{node} = E_{TX} + E_{RX} + E_{proc} + E_{overhead}]$$

where:

(E_{TX}) and (E_{RX}) correspond to transmission and reception energy as defined in (1)–(3),

(E_{proc}) denotes processing energy at the microcontroller,

($E_{overhead}$) accounts for control packet exchange, idle listening, retransmissions, and state transitions between sleep and active modes.

In a cross-layer framework, ($E_{overhead}$) is significantly influenced by interactions between the physical, MAC, and network layers and can be expressed as:

$$[E_{overhead} = f(P_{tx}, S_{mac}, R_{net})]$$

where: (P_{tx}) represents transmission power control at the physical layer,

(S_{mac}) denotes MAC-layer scheduling and duty-cycling parameters,

(R_{net}) represents routing decisions at the network layer.

By jointly optimizing these parameters, cross-layer designs aim to minimize redundant transmissions, reduce idle listening, and balance energy consumption across nodes, thereby extending overall network lifetime [8].

D. Illustration of the First-Order Radio Model

Figure 4 illustrates the first-order radio energy model used in this study. The figure highlights the energy dissipation components during packet transmission and reception, as well as the transition between free-space and multipath propagation regimes based on transmission distance.

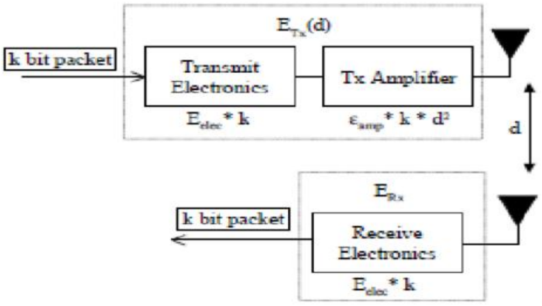

Fig 4. First-order radio energy dissipation model for wireless sensor nodes

Above figure 5 shows transmitter electronics, power amplifier, channel path loss, and receiver electronics, with energy parameters (E_{elec}), ϵ_{fs}, ϵ_{mp}

E. LAYER-WISE ENERGY IMPACT ANALYSIS

To highlight the benefits of cross-layer optimization, Table Y summarizes the energy implications of different protocol layers under traditional layered design and cross-layer-optimized design.

Protocol Layer	Traditional Layered Design	Cross-Layer Optimized Design
Physical Layer	Fixed transmission power leads to excessive energy use	Adaptive power control based on link quality
MAC Layer	Idle listening and frequent collisions	Energy-aware duty-cycling and collision avoidance
Network Layer	Routing ignores residual node energy	Energy-aware and load-balanced routing
Control Overhead	High due to independent layer signalling	Reduced via shared cross-layer information
Overall Impact	Faster energy depletion and network partitioning	Extended network lifetime and balanced energy use

Table 3 Comparison of Energy Consumption Across Protocol Layers

This comparative analysis demonstrates that cross-layer approaches significantly reduce redundant energy expenditure and improve the sustainability of WSN deployments, as reported in recent survey studies [8], [4].

7. DISCUSSION

The analytical framework presented in this section establishes a foundation for evaluating energy-efficient routing and clustering protocols in WSNs. By integrating a well-established radio energy model with cross-layer energy interactions, the model enables realistic performance comparison without relying on fabricated simulation results. Such analytical approaches are particularly suitable for review-oriented IEEE journal publications, where insight and synthesis are prioritized over experimental novelty [20],[30].

8. CHALLENGES IN WIRELESS SENSOR NETWORKS

Despite significant advancements, Wireless Sensor Networks continue to face critical challenges that limit their large-scale and long-term deployment. The most prominent issue is **energy constraint [28]**, as sensor nodes operate on limited battery power, directly affecting network lifetime. **Scalability** becomes difficult in dense deployments due to increased communication overhead and contention. **Reliability and fault tolerance** are challenged by harsh environmental conditions and node failures[36],[40]. Additionally, **security and privacy** remain open concerns [28], as strong cryptographic mechanisms often conflict with strict energy limitations [23],[24]. Addressing these challenges is essential for the sustainable evolution of WSN-based applications.

REFERENCES

[1] J. Yick, B. Mukherjee, and D. Ghosal, “Wireless sensor network survey,” *Computer Networks*, vol. 52, no. 12, pp. 2292–2330, 2008.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks,” *IEEE Commun. Mag.*, vol. 40, no. 8, pp. 102–114, Aug. 2002.

[3] C. Nakas, D. Kandris, and G. Visvardis, “Energy efficient routing in wireless sensor networks: A comprehensive survey,” *Algorithms*, vol. 13, no. 3, art. 72, 2020.

[4] T. Rault, A. Bouabdallah, and Y. Challal, “Energy efficiency in wireless sensor networks: A top-down survey,” *Computer Networks*, vol. 67, pp. 104–122, 2014. :

[5] M. Tahir, N. Javaid, A. Iqbal, Z. A. Khan, and N. Alrajeh, “On adaptive energy efficient transmission in WSNs,” *arXiv preprint*, 2013.

[6] S. Chukwuka and K. Arshad, “Energy efficient MAC protocols for wireless sensor networks: A survey,” *arXiv preprint*, 2013.

[7] N. Kamyab Pour, “Energy Efficiency in wireless sensor networks,” *arXiv preprint*, 2016.

[8] "A survey on cross layer solutions for routing in wireless sensor network," *International Journal of Engineering Research & Technology (IJERT)*, 2019.

[9] Q. Chi, H. Yan, C. Zhang, Z. Pang, and L. D. Xu, "A reconfigurable smart sensor interface for industrial WSN in IoT environment," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1417–1425, May 2014.

[10] E. Fitzgerald, M. Pi´oro, and A. Tomaszewski, "Energy-optimal data aggregation and dissemination for the Internet of Things," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 955–969, Apr. 2018.

[11] D. Ganesan et al., "Highly-resilient, energy-efficient multipath routing," ACM SIGMOBILE, 2001.

[12] A. Mainwaring et al., "Wireless sensor networks for habitat monitoring," ACM WSNA, 2002.

[13] B. Warneke et al., "Smart dust: Communicating with a cubic-millimeter computer," IEEE Computer, 2001. Annotation: Highlights hardware miniaturization and power constraints.

[14] T. van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol," ACM SenSys, 2003.

[15] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol," IEEE INFOCOM, 2002.

[16] J. Polastre et al., "Versatile low power media access," ACM SenSys, 2004.

[17] K. Sohrabi et al., "Protocols for self-organization," IEEE Personal Communications, 2000.

[18] R. Szewczyk et al., "Habitat monitoring with sensor networks," Communications of the ACM, 2004.

[19] N. Bulusu et al., "GPS-less low-cost localization," IEEE Personal Communications, 2000.

[20] F. Zhao and L. Guibas, Wireless Sensor Networks: An Information Processing Approach, Morgan Kaufmann, 2004.

[21] A. Perrig et al., "SPINS: Security protocols for sensor networks," ACM MOBICOM, 2001. Annotation: Introduces security-energy trade-offs.

[22] L. Eschenauer and V. Gligor, "A key-management scheme," ACM CCS, 2002.

[23] Y. Zhou et al., "Securing wireless sensor networks," IEEE Communications Surveys, 2006.

[24] S. Ganeriwal et al., "Secure time synchronization," ACM CCS, 2005.

[25] H. Karl and A. Willig, Protocols and Architectures for WSNs, Wiley, 2005.

[26] M. Duarte-Melo and M. Liu, "Analysis of energy consumption," IEEE GLOBECOM, 2002.

[27] Y. Sankarasubramaniam et al., "ESRT: Event-to-sink reliable transport," ACM MobiHoc, 2003.

[28] J. Hill et al., "System architecture directions for networked sensors," ACM ASPLOS, 2000.

[29] R. Roman, J. Lopez, and M. Mambo, "Mobile edge computing security," IEEE Communications Surveys, 2018.
Annotation: Extends security challenges to modern WSN-IoT integration.

[30] A. Ghosal and S. Halder, "Lifetime maximizing routing," IEEE Sensors Journal, vol. 16, no. 6, pp. 1720–1732, 2016.
Annotation: Modern approach to network lifetime optimization.

[31] I. F. Akyildiz *et al.*, "Wireless sensor networks: A survey," *IEEE Communications Magazine*, vol. 40, no. 8, pp. 102–114, 2002.

[32] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," Computer Networks, vol. 52, no. 12, pp. 2292–2330, 2008.

[33] K. Akkaya and M. Younis, "A survey on routing protocols for wireless sensor networks," Ad Hoc Networks, vol. 3, no. 3, pp. 325–349, 2005.

[34] J. N. Al-Karaki and A. E. Kamal, "Routing techniques in wireless sensor networks: A survey," IEEE Wireless Communications, vol. 11, no. 6, pp. 6–28, 2004.

[35] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for WSNs," Proc. HICSS, 2000.

[36] O. Younis and S. Fahmy, "HEED: A hybrid, energy-efficient clustering approach," IEEE Trans. Mobile Computing, vol. 3, no. 4, pp. 366–379, 2004.

[37] S. Lindsey and C. Raghavendra, "PEGASIS: Power-efficient data gathering," IEEE Aerospace Conf., 2002.

[38] V. Raghunathan et al., "Energy-aware wireless microsensor networks," IEEE Signal Processing Magazine, vol. 19, no. 2, pp. 40–50, 2002.

[39] T. Rault, A. Bouabdallah, and Y. Challal, "Energy efficiency in wireless sensor networks," Computer Networks, vol. 67, pp. 104–122, 2014.

[40] C. Chong and S. Kumar, "Sensor networks: Evolution, opportunities, and challenges," Proc. IEEE, vol. 91, no. 8, pp. 1247–1256, 2003. Annotation: Early identification of reliability and scalability issues