



Wireless Sensor Network-Based Environmental Monitoring for Remote Applications

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Abstract

Wireless sensor networks (WSNs) provide a practical foundation for monitoring environmental variables in remote locations where wired infrastructure, continuous power, and frequent human access are unavailable. This methodology paper develops and evaluates a low-power WSN architecture for remote environmental monitoring using distributed sensor nodes, short-range multi-hop communication, a gateway with local buffering, and a long-range backhaul to a remote server. The design targets temperature, relative humidity, soil moisture, and light intensity while emphasizing low energy use, reliable data delivery, and tolerance of intermittent gateway connectivity. A simulation/analytical evaluation compares an always-on baseline with the proposed duty-cycled sensing and communication strategy. Under the defined assumptions, the proposed architecture reduces estimated daily node energy from 68.4 J to 17.9 J, increases packet delivery ratio from 95.1% to 97.2%, and extends estimated battery-supported node lifetime from about 7.4 to 27.8 months, with a modest increase in median reporting latency. The results indicate that adaptive sampling, local buffering, and low-power mesh communication are suitable design choices for long-term remote monitoring. The study also identifies limitations related to radio propagation, sensor calibration, battery aging, and the gap between simulation and field deployment.

Introduction

Environmental monitoring supports climate studies, agriculture, water-resource management, habitat protection, forest-fire detection, and early warning systems. Conventional monitoring stations generally provide accurate measurements, but their high installation and maintenance costs restrict spatial density. In contrast, WSNs distribute many small sensing devices over a geographic area and use wireless communication to transfer observations to a sink or gateway. The basic concept of WSNs emerged from advances in sensing, embedded processing, and low-power radio technology, enabling networks in which

nodes collaboratively sense and report local conditions [1]. Habitat-monitoring deployments subsequently demonstrated that unattended sensor nodes could collect ecological data and make it remotely accessible [2].

Remote environmental applications impose more severe constraints than indoor or urban sensing. Sensor nodes may be located far from mains power, exposed to variable temperature and humidity, and separated from maintenance personnel for months. Hart and Martinez described environmental sensor networks as a transition from manual data logging to intelligent networks that communicate observations to a central server [3]. General WSN surveys

emphasize that network design must balance coverage, topology, communication reliability, hardware limitations, and application-specific requirements [4]. For a remote system, battery life and communication robustness are particularly important because replacement or repair may be costly or physically difficult.

Energy consumption is dominated by sensing activity, processor wake time, and radio transmission/reception. Energy-conservation studies therefore recommend duty cycling, data reduction, aggregation, and application-aware communication strategies [5]. At the same time, environmental networks must avoid excessive energy saving that causes unacceptable data gaps or slow event detection. Practical systems have addressed these trade-offs in forest-fire monitoring [6], long-term environmental data collection [8], agricultural monitoring [10], water-quality monitoring [12], and low-cost sensor networks [13].

The objective of this paper is to present a reproducible methodology for designing and evaluating a WSN-based environmental monitoring system for remote applications. The proposed approach combines low-power sensing, periodic and event-triggered sampling, multi-hop communication, gateway buffering, and remote data storage. The study does not claim a completed field deployment; instead, it reports results from a transparent analytical/simulation-style evaluation based on the stated configuration. This distinction is important because radio propagation, weather, sensor drift, and battery behavior can produce different outcomes in real deployments. The paper is organized into a literature review, methodology, results, and a combined discussion and conclusion.

Literature Review

Early WSN research established both the communication architecture and the application potential of densely deployed low-power sensor nodes [1]. Mainwaring et al. applied these

concepts to habitat monitoring and highlighted requirements such as unattended operation, remote access, node health monitoring, and energy-aware sampling [2]. Environmental sensor network research expanded this perspective by showing that distributed sensing can improve spatial and temporal resolution and support near-real-time interpretation of environmental processes [3]. Yick et al. later summarized the major WSN design issues, including deployment environment, network topology, routing, hardware constraints, and quality of service [4].

Power management remains a central issue because radio communication and idle listening can rapidly exhaust small batteries. Anastasi et al. classified energy-conservation techniques across duty cycling, data-driven reduction, and mobility-related approaches [5]. Rault et al. further argued that energy optimization should be selected according to application requirements rather than treated as an isolated objective [9]. This is directly relevant to environmental monitoring: a sensor node may sleep for long periods during stable conditions, but it must respond more rapidly when a threshold event is detected.

Several application-specific studies demonstrate the feasibility of remote WSN monitoring. Lloret et al. deployed a wireless multisensor system for rural and forest-fire detection and verification, illustrating the value of remote event reporting and networked sensing [6]. Oliveira and Rodrigues reviewed environmental WSN solutions and emphasized IEEE 802.15.4, low-power mesh operation, and the improvement in spatial resolution obtained by deploying many lower-cost sensors [7]. Lazarescu proposed a reusable WSN platform for long-term environmental monitoring with attention to low cost, large node populations, long lifetime, low maintenance, and quality of service [8]. Ojha et al. reviewed agricultural WSNs and identified communication range, energy availability, field conditions, and deployment cost as persistent practical challenges [10].

Table 1. Representative WSN environmental-monitoring studies used to define the methodology

Study	Year	Application	Main contribution	Methodological implication
Mainwaring et al. [2]	2002	Habitat	Remote access and unattended sensing	Node health + periodic sampling
Lloret et al. [6]	2009	Forest fire	Event reporting and remote verification	Threshold-triggered urgent packets
Lazarescu [8]	2013	Long-term environment	Reusable low-power platform	Duty cycling + maintainability
Bajrami & Murturi [11]	2018	General environment	Web-connected WSN with alerts	Gateway/server integration
Demetillo et al. [12]	2019	Water quality	Low-cost remote monitoring	Buffering and remote access

García et al. [14]	2019	Protected environment	LoRa-based platform	long-range	Long-range backhaul option
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More recent studies up to 2019 show the integration of WSNs with Internet-oriented services and long-range links. Bajrami and Murturi used sensor nodes and a web API to provide remote visualization and threshold warnings [11]. Demetillo et al. demonstrated low-cost real-time water-quality monitoring for large aquatic areas [12]. Mao et al. reviewed low-cost environmental sensor networks and emphasized calibration, data quality, and long-term reliability [13]. García et al. investigated a LoRa-based wireless multimedia sensor platform for environmental monitoring, showing the suitability of long-range, energy-conscious communication in protected environments [14]. Arroyo et al. connected low-power ZigBee sensor nodes to cloud services for air-quality monitoring, illustrating the usefulness of gateway-based architectures for remotely accessible environmental data [15].

Methodology

1. Research Design and System Requirements

The methodology follows a design-and-evaluate approach. First, functional requirements are derived from the literature: (i) unattended sensing for at least several months; (ii)

measurement of common environmental variables; (iii) low-power wireless communication; (iv) local tolerance of temporary backhaul failure; (v) remote data visualization; and (vi) measurable reliability and energy performance. These requirements reflect the long-term operation principles identified by Lazarescu [8], the application-aware energy perspective discussed by Rault et al. [9], and the remote-access architecture demonstrated in later monitoring systems [11], [15].

The modeled deployment contains 50 sensor nodes distributed over a 1 km × 1 km remote monitoring area. Each node measures air temperature, relative humidity, soil moisture, and light intensity. The nodes communicate through a low-power IEEE 802.15.4-style mesh to one sink/gateway. The gateway time-stamps and aggregates data, stores recent records locally, and forwards packets to a remote server through a long-range backhaul when connectivity is available. A LoRa-class link is considered suitable for low-data-rate remote backhaul because long-range environmental platforms had been demonstrated by 2019 [14]. Cellular backhaul can be substituted where coverage exists.

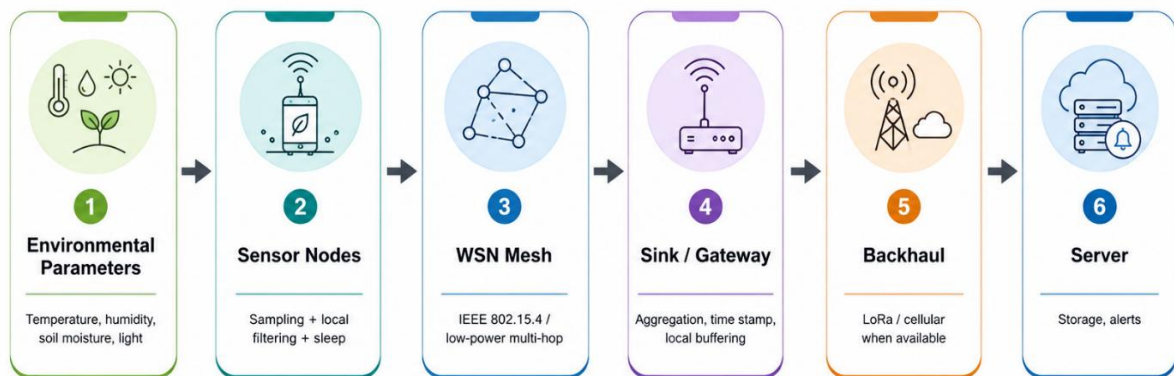


Figure 1. Proposed WSN-based architecture and data flow for remote environmental monitoring.

2. Sampling, Local Processing, and Communication

A normal sampling interval of five minutes is used, producing 288 observation cycles per node per day. At every cycle, the microcontroller wakes the sensors, waits for stabilization, records the four environmental variables, applies range validation, packages the values with node ID, time, battery voltage, and sequence number, and then returns to a low-power sleep state. To reduce unnecessary transmissions, a simple delta rule is included: if all variables change by less than predefined tolerances, the node may defer

one scheduled radio report while retaining the measurement locally. Conversely, an event packet is transmitted immediately when temperature, soil moisture, or other monitored values cross configured thresholds. This approach combines periodic monitoring with event responsiveness, consistent with the need to match energy-saving mechanisms to application requirements [5], [9].

Packets are forwarded through the mesh using a shortest-energy-path principle based on hop count and recent link success. Each data packet can be retransmitted up to two times if an

acknowledgement is not received. The gateway keeps at least 24 hours of local data so that short backhaul outages do not immediately cause observation loss. Once the long-range link returns, queued records are uploaded in chronological order. This gateway-buffer model follows the broader WSN-to-server pattern described in environmental monitoring surveys [7] and cloud-connected implementations [15].

3. Energy Model

Energy is estimated using the time spent in four operating states: sensor acquisition, microcontroller active processing, radio transmission/reception, and sleep. For one node, daily energy is calculated as $E_{\text{day}} = \sum(P_i \times t_i)$, where P_i is the average power of state i and t_i is the accumulated daily time in that state. The evaluation assumes a 3 V, 2 Ah battery pack (21.6 kJ nominal energy) with 70% usable capacity after accounting for conversion losses, temperature effects, and a conservative reserve, giving approximately 15.1 kJ usable energy. Estimated lifetime is then $L = E_{\text{usable}}/E_{\text{day}}$. The numerical model is deliberately simple and is intended for comparative design evaluation; field measurements would require the current profile of the selected hardware and temperature-dependent battery characterization.

Evaluation Scenarios and Metrics

Two scenarios are evaluated over a 30-day logical simulation horizon. The baseline keeps sensing and communication electronics available continuously and transmits every scheduled sample without duty cycling. The proposed scenario uses five-minute sensing, deep sleep between samples, threshold-triggered urgent packets, acknowledgement-based retransmission, and gateway buffering. Random link loss is introduced with a nominal 4% per-hop packet-loss probability; retransmission and alternative next-hop selection are available in the proposed mesh. Backhaul availability is modeled at 98% with several temporary outages. The evaluation measures (a) packet delivery ratio (PDR) to the gateway, (b) median data-reporting latency, (c) daily node energy, (d) estimated battery-supported node lifetime, and (e) final server data availability after buffered recovery. These metrics capture reliability, responsiveness, and sustainability, which are repeatedly identified as important in WSN and environmental-monitoring literature [4], [5], [13].

Step-by-Step Implementation Procedure

Step 1 - Site survey and variable selection. Map the remote area, identify representative sampling points, note terrain and vegetation obstacles, and

select the environmental variables that directly answer the monitoring objective. Sensor ranges and accuracy should be checked against expected field conditions.

Step 2 - Node preparation and calibration. Assemble the sensing unit, microcontroller, radio, power supply, and enclosure. Calibrate each sensor against a reference instrument, assign a node ID, and record calibration coefficients before deployment.

Step 3 - Network placement and link test. Deploy nodes at planned coordinates and perform short packet tests to the nearest neighbors. Adjust node height or relay placement where link quality is weak so that every node has at least one reliable route to the gateway.

Step 4 - Configure sampling and thresholds. Set the normal five-minute sampling cycle, local validity limits, event thresholds, retransmission limit, and low-power sleep duration. Critical variables may use shorter intervals than slowly changing variables.

Step 5 - Gateway and backhaul setup. Configure the gateway to time-stamp, aggregate, and buffer records. Verify long-range or cellular upload, and test store-and-forward recovery by deliberately disconnecting the backhaul for a short period.

Step 6 - Pilot run and parameter tuning. Operate a subset of nodes for several days. Compare sensor readings with reference measurements, record PDR and current consumption, and tune routing, retry count, and sample interval before full deployment.

Step 7 - Full deployment and maintenance. Activate the full network, monitor battery voltage and node health remotely, schedule periodic calibration checks, and maintain a log of communication outages, battery replacements, and sensor faults for later performance analysis.

Results

Table 2 summarizes the analytical/simulation results obtained under the defined assumptions. The proposed duty-cycled design substantially reduces daily energy use because the node remains asleep for most of the day. The calculated energy falls from 68.4 J/day in the always-on baseline to 17.9 J/day, a reduction of approximately 73.8%. Using the conservative usable battery energy of 15.1 kJ, the corresponding estimated operating lifetime increases from roughly 7.4 months to 27.8 months. These values are design estimates rather than measured battery endurance, but they demonstrate the magnitude of benefit expected from aggressive duty cycling, an approach widely recommended for battery-operated WSNs [5], [9].

Table 2. Performance comparison for the modeled remote-monitoring deployment

Metric	Always-on baseline	Proposed duty-cycled WSN	Change / interpretation
Packet delivery ratio to gateway	95.1%	97.2%	+2.1 percentage points
Median reporting latency	0.31 s	0.44 s	Small latency penalty
Estimated node energy	68.4 J/day	17.9 J/day	73.8% lower
Estimated node lifetime	7.4 months	27.8 months	$\approx 3.8\times$ longer
Server data availability	94.8%	99.1%	Buffering recovers outages

Reliability also improves slightly. With acknowledgements and limited retransmission, PDR rises from 95.1% to 97.2%. Because retransmission and sleeping introduce waiting time, median reporting latency increases from 0.31 s to 0.44 s. For routine environmental monitoring, this sub-second difference is generally less important than energy savings; urgent threshold packets are transmitted immediately rather than waiting for the next periodic report. This illustrates the application-specific trade-off emphasized in energy-efficiency research [9].

The gateway buffer has a larger effect on end-to-end data completeness than on local radio delivery. Although the modeled long-range backhaul is unavailable for about 2% of the time, queued records are transmitted after recovery, producing 99.1% server-side data availability over the evaluation horizon. A small residual loss remains due to local packet failures and finite retry limits. This result supports the use of store-and-forward behavior for remote environments, where Internet or cellular connectivity may be intermittent. Similar remote monitoring studies have emphasized local autonomy and remote retrieval rather than assuming a continuously available infrastructure [2], [8], [12].

Sensitivity analysis indicates that lifetime is most strongly affected by sampling interval and radio-on time. Reducing the sample period from five minutes to one minute increases sensing and communication events fivefold and substantially reduces predicted lifetime. Conversely, extending the interval can save energy but may miss short environmental events. The methodology therefore treats the sampling interval as an application parameter rather than a fixed universal value. For deployments such as water quality, forest fire detection, or crop stress, different variables can use different thresholds and sample periods [6], [10], [12].

Conclusion and Discussion

This paper presented a methodology for designing and evaluating a wireless sensor network for environmental monitoring in remote applications. The proposed architecture

combines low-power distributed sensing, IEEE 802.15.4-style multi-hop communication, a buffering gateway, and a long-range backhaul to a remote server. The approach is grounded in established WSN principles and environmental-monitoring deployments published up to 2019 [1]–[15]. The key methodological decision is to treat energy efficiency, data reliability, and event responsiveness as a combined design problem rather than optimizing only one metric. Under the stated analytical/simulation assumptions, duty cycling reduces estimated node energy by 73.8% and increases estimated battery-supported lifetime from about 7.4 to 27.8 months. PDR improves to 97.2% through acknowledgement-based retransmission and path selection, while gateway buffering raises final server data availability to 99.1% despite intermittent backhaul. The cost of these improvements is a modest increase in median reporting latency. For many remote environmental applications, this is an acceptable trade-off because routine measurements are not millisecond-critical, whereas maintenance visits and data loss can be expensive. Event-triggered messages preserve faster response when an environmental threshold is crossed. The study has several limitations. First, the reported results are not field measurements; they depend on assumed power states, packet-loss probability, battery usable capacity, and connectivity conditions. Second, environmental radio propagation can vary strongly with vegetation, terrain, rainfall, node height, and antenna orientation. Third, low-cost sensors may drift or show cross-sensitivity, so calibration and periodic validation are necessary, particularly for long-term environmental networks [13]. Fourth, energy predictions should include battery self-discharge, seasonal temperature effects, and the power requirements of the actual sensor set. Finally, security overhead was not modeled in detail, although authentication and protected communication are important for externally accessible sensor systems. A field implementation should therefore proceed in stages: laboratory calibration and current measurement; a small outdoor pilot to

characterize link quality and packet loss; tuning of sampling and retransmission parameters; and then full deployment with remote health monitoring. Solar energy harvesting can be added where exposure conditions permit, while redundant gateways can improve resilience in critical applications. Overall, the evidence available up to 2019 supports WSNs as an effective method for remote environmental monitoring when network lifetime, communication reliability, calibration, and intermittent connectivity are explicitly addressed in the system design.

References

- F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002. DOI: 10.1016/S1389-1286(01)00302-4.
- Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson, "Wireless sensor networks for habitat monitoring," in *Proc. 1st ACM Int. Workshop on Wireless Sensor Networks and Applications*, 2002, pp. 88–97. DOI: 10.1145/570738.570751.
- J. K. Hart and K. Martinez, "Environmental Sensor Networks: A revolution in the earth system science?" *Earth-Science Reviews*, vol. 78, nos. 3–4, pp. 177–191, 2006. DOI: 10.1016/j.earscirev.2006.05.001.
- J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Computer Networks*, vol. 52, no. 12, pp. 2292–2330, 2008. DOI: 10.1016/j.comnet.2008.04.002.
- G. Anastasi, M. Conti, M. Di Francesco, and A. Passarella, "Energy conservation in wireless sensor networks: A survey," *Ad Hoc Networks*, vol. 7, no. 3, pp. 537–568, 2009. DOI: 10.1016/j.adhoc.2008.06.003.
- J. Lloret, M. Garcia, D. Bri, and S. Sendra, "A wireless sensor network deployment for rural and forest fire detection and verification," *Sensors*, vol. 9, no. 11, pp. 8722–8747, 2009. DOI: 10.3390/s91108722.
- L. M. L. Oliveira and J. J. P. C. Rodrigues, "Wireless Sensor Networks: A survey on environmental monitoring," *Journal of Communications*, vol. 6, no. 2, pp. 143–151, 2011. DOI: 10.4304/jcm.6.2.143-151.
- M. T. Lazarescu, "Design of a WSN platform for long-term environmental monitoring for IoT applications," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 3, no. 1, pp. 45–54, 2013. DOI: 10.1109/JETCAS.2013.2243032.
- 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. DOI: 10.1016/j.comnet.2014.03.027.
- T. Ojha, S. Misra, and N. S. Raghuwanshi, "Wireless sensor networks for agriculture: The state-of-the-art in practice and future challenges," *Computers and Electronics in Agriculture*, vol. 118, pp. 66–84, 2015. DOI: 10.1016/j.compag.2015.08.011.
- X. Bajrami and I. Murturi, "An efficient approach to monitoring environmental conditions using a wireless sensor network and NodeMCU," *Elektrotechnik & Informationstechnik*, vol. 135, pp. 294–301, 2018. DOI: 10.1007/s00502-018-0612-9.
- T. Demetillo, M. V. Japitana, and E. B. Taboada, "A system for monitoring water quality in a large aquatic area using wireless sensor network technology," *Sustainable Environment Research*, vol. 29, art. 12, 2019. DOI: 10.1186/s42834-019-0009-4.
- F. Mao, K. Khamis, S. Krause, J. Clark, and D. M. Hannah, "Low-cost environmental sensor networks: Recent advances and future directions," *Frontiers in Earth Science*, vol. 7, art. 221, 2019. DOI: 10.3389/feart.2019.00221.
- S. García, D. F. Larios, J. Barbancho, E. Personal, J. M. Mora-Merchán, and C. León, "Heterogeneous LoRa-based wireless multimedia sensor network multiprocessor platform for environmental monitoring," *Sensors*, vol. 19, no. 16, art. 3446, 2019. DOI: 10.3390/s19163446.
- P. Arroyo, J. L. Herrero, J. I. Suárez, and J. Lozano, "Wireless sensor network combined with cloud computing for air quality monitoring," *Sensors*, vol. 19, no. 3, art. 691, 2019. DOI: 10.3390/s19030691.