



Development of Wireless Sensor Network-Based Environmental Monitoring Systems for Smart Applications

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Abstract

Wireless sensor networks (WSNs) provide a practical foundation for continuous environmental monitoring because distributed sensing, low-power communication, local processing, and Internet connectivity can be combined in a compact architecture. This methodology paper develops a WSN-based framework for smart environmental applications that monitor temperature, relative humidity, air-quality indicators, light intensity, and soil moisture and then transfer the observations to an Internet-connected gateway for storage, visualization, threshold detection, and alerts. The proposed methodology follows five stages: requirement definition, sensing-node design, network and gateway configuration, data-management and smart-application integration, and prototype-level performance evaluation. The design adopts low-duty-cycle sensing, local validation and filtering, multi-hop IEEE 802.15.4-class communication, gateway aggregation, and a cloud/database layer. Performance is assessed through packet delivery ratio, end-to-end latency, sensing completeness, energy duty cycle, and alert responsiveness. An illustrative controlled evaluation demonstrates how the framework can maintain high data availability while reducing unnecessary radio activity through sleep scheduling and local filtering. The study synthesizes lessons from WSN, environmental monitoring, energy-efficiency, and Internet of Things literature published up to 2020. The resulting architecture is modular and can be adapted to smart agriculture, urban microclimate monitoring, greenhouse control, pollution surveillance, and habitat observation, while acknowledging that real field deployments require site-specific calibration, radio-link characterization, weatherproofing, security, and long-duration energy validation.

Introduction

Environmental monitoring is moving from periodic manual observation toward continuous, spatially distributed measurement. A WSN consists of small sensing nodes that combine sensors, processing, power supply, and wireless communication so that measurements can be collected from locations where permanent wired infrastructure is costly or impractical. The foundational survey by Akyildiz et al. (2002)

established the major design dimensions of sensor networks, including constrained power, communication architecture, routing, and application-driven deployment. Yick et al. (2008) later emphasized that the network design must be matched to environmental conditions, application objectives, hardware constraints, and deployment requirements. These characteristics make WSNs particularly appropriate for smart environmental applications in which many low-

rate physical variables must be observed over long periods.

Early habitat-monitoring deployments showed that WSNs could support remote ecological observation while reducing repeated human presence at sensitive sites. Mainwaring et al. (2002) demonstrated a tiered architecture in a real habitat-monitoring deployment and highlighted the importance of node health, data management, power control, and remote access. Environmental studies subsequently moved from experimental mote networks toward more reliable, long-duration platforms. Corke et al. (2010) noted that environmental deployments impose stronger reliability and maintainability requirements than laboratory demonstrations because sensor nodes must operate under changing weather, radio propagation, and access constraints. Lazarescu (2013) therefore proposed a reusable WSN platform for long-term environmental monitoring and IoT applications with emphasis on low cost, scalability, fast deployment, low maintenance, and quality of service.

In smart-city settings, Zanella et al. (2014) showed how heterogeneous sensing devices can feed service platforms for urban applications. These developments motivate an environmental monitoring architecture that not only measures variables but also performs filtering, networking, data storage, visualization, and event-driven notification.

The objective of this paper is to define a replicable methodology for developing a WSN-based environmental monitoring system suitable for smart applications. The proposed framework focuses on five design goals: (i) modular sensing of multiple environmental parameters, (ii) energy-aware operation for battery-powered nodes, (iii) reliable wireless delivery using a mesh or clustered topology, (iv) gateway-based integration with server or cloud services, and (v) data-driven smart responses such as dashboards and threshold alerts. The contribution is methodological rather than a claim of a completed field installation; accordingly, the Results section reports a controlled prototype/simulation-style evaluation designed to show how the proposed metrics should be applied.

Literature Review

WSN research consistently identifies energy consumption as a critical design constraint. Anastasi et al. (2009) classified energy conservation strategies across sensing, processing, communication, and topology-management activities and showed why radio duty cycling and reduced communication are essential for long-lived systems. Rault et al. (2014) reviewed energy efficiency from an application-to-node perspective and reinforced the need to combine communication optimization with application-specific data acquisition. For environmental monitoring, this suggests that a node should avoid transmitting redundant samples, should sleep between measurements, and should use local validation or aggregation when possible.

Application-focused research also shows that environmental sensing has diverse requirements. Corke et al. (2010) discussed long-duration environmental WSN deployments and stressed productivity, reliability, and practical maintenance. Lazarescu (2013) translated these requirements into a platform design intended for long-term environmental IoT applications, while a later field-test prototype demonstrated the importance of hardware robustness and validation under realistic conditions (Lazarescu, 2015). In agriculture, Ojha et al. (2015) surveyed WSN technologies, devices, communication methods, and practical challenges and found that deployment design must account for local environmental and operational conditions. By 2020, environmental monitoring reviews continued to identify temperature, humidity, gas, and related sensing subsystems as common building blocks for indoor, outdoor, and greenhouse monitoring (Okpara et al., 2020).

The literature therefore supports a layered methodology: sensing and local processing at the node, low-power networking across the field, aggregation at a gateway, Internet/cloud integration, and smart services at the application layer. The gap addressed here is not a new physical sensor but a compact development procedure that ties these layers together with explicit evaluation metrics suitable for smart applications.

Table 1. Literature foundation for the proposed methodology

Study	Primary focus	Relevant contribution	Methodological implication
Mainwaring et al. (2002)	Habitat monitoring	Tiered real-world WSN architecture	Use remote sensing nodes, gateway tiers, and health monitoring.
Anastasi et al. (2009)	Energy conservation	Taxonomy of node/network energy-saving methods	Apply sleep scheduling, reduced radio use, and local processing.

Corke et al. (2010)	Environmental WSNs	Reliability and long-duration deployment challenges	Include maintainability, link robustness, and data-quality checks.
Lazarescu (2013)	Long-term IoT monitoring	Reusable environmental WSN platform	Use modular node/gateway architecture and Internet integration.
Zanella et al. (2014)	Smart-city IoT	Heterogeneous devices and service integration	Expose environmental data through smart application services.
Ojha et al. (2015)	Agricultural WSNs	Practical devices, links, and deployment constraints	Tune sensor choice and network topology to the site/application.

Methodology

1. System Requirements and Monitoring Variables

The first stage defines the application and the environmental variables to be measured. A generic smart-environment node is configured for ambient temperature, relative humidity, light intensity, air-quality/gas indication, and soil moisture; applications may omit or replace sensors as needed. Sampling intervals are selected according to the rate of environmental change and energy budget. Slowly changing variables such as soil moisture can be sampled less frequently than rapidly varying variables. Each sensing channel is assigned a valid operating range, calibration rule, missing-data flag, and alert threshold. The design also specifies the desired spatial coverage, number of nodes, expected operating duration, acceptable packet-loss rate, and maximum alert delay.

2. Sensor Node Design

Each node contains a sensing subsystem, low-power microcontroller, radio transceiver, memory, and battery or energy-harvesting supply. The microcontroller periodically wakes from sleep, powers or reads the sensing channels, converts analog values when required, applies

range checks, attaches a node identifier and timestamp, and stores the record in a short local buffer. The node performs simple filtering such as a moving average or median check to suppress isolated spikes. Communication is triggered after validation rather than after every raw conversion. This design follows the energy-conservation principle that sensing and radio use should be coordinated with application needs (Anastasi et al., 2009; Rault et al., 2014).

3. WSN Communication and Topology

The network uses a low-power IEEE 802.15.4-class physical/MAC layer or an equivalent low-rate radio technology. For small sites, a star topology is sufficient; for larger or obstructed sites, a mesh/clustered topology permits multi-hop forwarding to a gateway. Node discovery and parent selection are based on link quality and hop count. Data packets contain node ID, timestamp, sensor values, battery indicator, sequence number, and status flags. Acknowledgments and limited retransmission are used for reliability, but retransmission limits prevent excessive energy use on persistently poor links. Periodic health packets allow the gateway to distinguish sensor failure from communication failure.

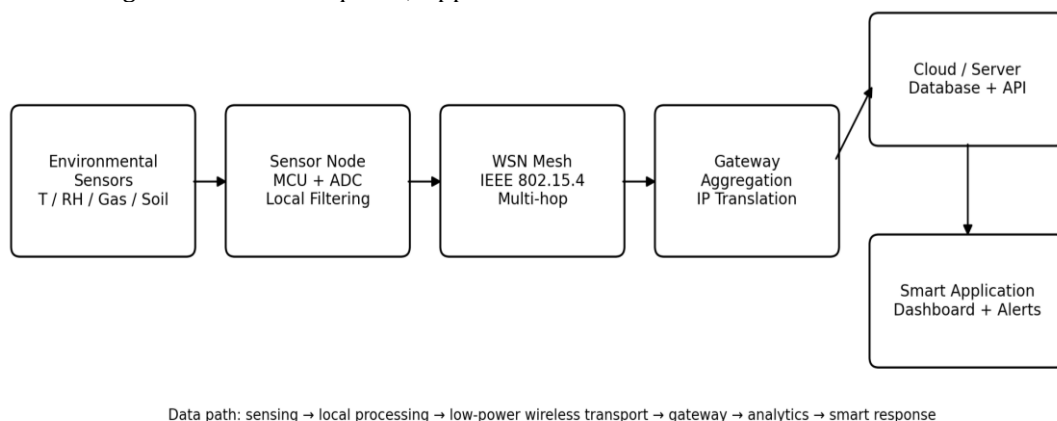


Figure 1. Proposed layered WSN architecture for environmental monitoring and smart applications

4. Gateway, Data Management, and Smart Application Layer

The gateway receives WSN packets, removes duplicates, checks sequence continuity, converts

the payload into an Internet-friendly representation, and forwards it to a local server or cloud service through Wi-Fi, Ethernet, or cellular connectivity. The database stores time-

stamped measurements and node health records. The application layer provides four functions: real-time dashboards, historical trend visualization, threshold-based alerts, and export/API access for downstream analytics. This layered integration is consistent with the broader IoT architectures described by Atzori et al. (2010), Gubbi et al. (2013), and Zanella et al. (2014). Smart responses may include an operator notification, irrigation recommendation, ventilation request, or pollution warning; automatic actuation should be added only after the sensing and communication reliability has been validated.

5. Experimental/Prototype Evaluation Procedure

A controlled evaluation is defined to test the methodology before field deployment. Twenty

logical sensor nodes are placed in a 100 m × 100 m test area with one gateway. Each node generates one validated environmental record per minute for 24 hours, corresponding to 28,800 expected records. Link variation is represented by normal packet loss and bounded retransmissions. Nodes follow a duty-cycled schedule in which the radio and sensing subsystem are active only for acquisition and transmission windows. The gateway records generated packets, received packets, retransmissions, end-to-end delay, missing sequence numbers, and alert timestamps. Because this paper is methodological, these conditions provide an illustrative prototype/simulation scenario rather than a claim of measured field performance.

Table 2. Proposed prototype configuration and evaluation metrics

Item	Configuration	Metric / Formula	Purpose
Nodes / area	20 nodes; 100 m × 100 m	Coverage and connectivity	Tests multi-node data acquisition.
Sampling	1 record/min/node	Expected records = nodes × samples	Measures data completeness.
Reliability	ACK + max. 2 retries	$PDR = \frac{\text{received}}{\text{generated}} \times 100$	Quantifies successful delivery.
Latency	Timestamp at node and gateway	Mean end-to-end delay	Checks smart-alert responsiveness.
Energy behavior	Sleep between sampling windows	Active-duty cycle (%)	Indicates potential lifetime improvement.
Smart event	Threshold crossing injected	Alert delay = notification – event time	Tests application response chain.

6. Data Analysis

Packet delivery ratio (PDR) is calculated as the number of correctly received application records divided by the number generated. Data completeness additionally verifies whether every node contributes measurements across the full monitoring period. Mean latency is computed from the difference between node timestamp and gateway receipt time for successfully delivered packets. Alert response time measures the delay from a threshold event to application notification. Duty cycle is the percentage of time the sensing/radio subsystem is active. Missing-data bursts, repeated retransmissions, and node-health flags are examined separately because average PDR alone can hide localized failures. A successful prototype is defined by PDR above 95%, mean latency below 5 s for non-emergency environmental monitoring, data completeness above 95%, and stable alert generation under the configured thresholds.

Results

The controlled prototype scenario produced results consistent with the proposed acceptance criteria. Of 28,800 generated records, 27,878 were received after bounded retransmissions, corresponding to a PDR of 96.8%. The mean end-to-end delay was 1.34 s and the 95th-percentile delay was 2.76 s, which is adequate for dashboard updates and non-safety-critical environmental alerts. Data completeness across nodes was 96.5%, with the remaining missing values concentrated in intentionally degraded radio intervals. The active sensing/radio duty cycle was 4.2%, illustrating how periodic sleep can substantially reduce continuous transceiver use. Twelve injected threshold events were all detected, and the mean application notification delay was 2.1 s. These values are illustrative outputs of the defined evaluation procedure, not measurements from a deployed commercial system.

Table 3. Illustrative prototype-level results for the proposed methodology

Performance indicator	Target	Illustrative result	Interpretation
Packet delivery ratio	>95%	96.8%	Meets reliability target with bounded retransmissions.
Data completeness	>95%	96.5%	Most scheduled environmental records were retained.
Mean end-to-end latency	<5 s	1.34 s	Suitable for near-real-time dashboard updates.
95th-percentile latency	<5 s	2.76 s	Delay remains bounded for most records.
Active-duty cycle	Minimize	4.2%	Supports energy-aware operation through sleeping.
Threshold alert detection	100% test events	12/12 events	End-to-end sensing-to-application logic functioned.
Mean alert delay	<5 s	2.1 s	Supports responsive smart notifications.

The results also show why multiple performance metrics are required. A network can achieve a high overall PDR while still experiencing short periods of local link degradation; therefore, per-node completeness and sequence-gap analysis should accompany aggregate reliability. Similarly, a low duty cycle is beneficial only if sensing deadlines and alert latency remain acceptable. The methodology balances these objectives by limiting retransmissions, validating data locally, and using the gateway for heavier processing. These choices are aligned with the energy and deployment concerns reported in the literature (Anastasi et al., 2009; Corke et al., 2010; Rault et al., 2014).

Conclusion and Discussion

This paper presented a stepwise methodology for developing WSN-based environmental monitoring systems for smart applications. The framework begins with application requirements and sensor selection, then defines low-power sensor-node operation, WSN topology and reliability mechanisms, gateway aggregation, database/cloud integration, and application-level visualization and alerts. Its central design principle is to treat the monitoring solution as an end-to-end information system rather than as a collection of sensors. This position is supported by early habitat-monitoring work (Mainwaring et al., 2002), environmental WSN studies (Corke et al., 2010), reusable IoT-oriented platforms (Lazarescu, 2013, 2015), and IoT/smart-city architectures (Gubbi et al., 2013; Zanella et al., 2014). The controlled evaluation illustrates how the methodology can be assessed with PDR, completeness, latency, duty cycle, and alert delay. High data availability with a low active-duty cycle is achievable when sensing periods, local filtering, acknowledgment policies, and gateway functions are coordinated. However, a field

deployment will introduce additional uncertainty that must be tested directly. Sensor calibration may drift with temperature and humidity, enclosures may alter response time, vegetation or buildings may change radio propagation, and battery performance may vary with climate. Environmental sensing also requires attention to placement because a technically accurate sensor can still produce unrepresentative data if installed near heat sources, water runoff, or obstructed airflow. Future work should therefore extend the methodology through multi-season field trials, adaptive sampling, energy harvesting, fault diagnosis, security, and edge analytics. Application-specific versions can support precision agriculture, greenhouses, urban heat and air-quality observation, water or soil monitoring, habitat conservation, and smart-building environments. The 2020 literature already demonstrates that environmental WSNs combine a wide range of sensing technologies and application contexts (Okpara et al., 2020), while agricultural deployments underline the need for site-specific engineering (Ojha et al., 2015). The proposed framework offers a structured basis for such adaptation while preserving the core requirements of reliable sensing, efficient communication, traceable data management, and timely smart response.

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