



Design and Implementation of a Wireless Sensor Network for Environmental Monitoring Applications

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Peer Review Information

Submission: 16 Dec 2019

Revision: 09 Jan 2020

Acceptance: 11 Feb 2020

Keywords

*Wireless Sensor Network,
Environmental Monitoring,
Low-Power Sensing,
ZigBee/LoRa, Sensor Node*

Abstract

Wireless sensor networks (WSNs) provide a practical framework for distributed environmental observation because they combine low-power sensing, short-range wireless communication, local computation, and remote data access. This methodology paper presents the design and implementation workflow for a low-cost WSN intended to monitor temperature, relative humidity, light intensity, and air-quality indicators in outdoor or semi-outdoor environments. The proposed system uses battery-powered sensor nodes, periodic sampling, local validation and filtering, a gateway for data aggregation, and a server-side database for storage and visualization. The methodology emphasizes sensor calibration, energy-aware duty cycling, packet-delivery reliability, network scalability, and repeatable field testing. A prototype-oriented evaluation procedure is defined using sensing accuracy, packet delivery ratio, end-to-end latency, node energy consumption, and estimated battery life. Illustrative prototype results indicate that the architecture can maintain high packet reliability while reducing radio-on time through duty-cycled operation. The design is grounded in environmental WSN studies published up to 2020 and is intended as a reproducible framework that can be adapted to agriculture, habitat, water-quality, urban, or building monitoring applications.

Introduction

Environmental monitoring requires measurements that are spatially distributed, temporally frequent, and available with minimal manual intervention. Conventional monitoring stations can provide high-accuracy measurements, but the cost of dense deployment and repeated data collection often limits spatial resolution. Wireless sensor networks address this gap by deploying multiple low-cost nodes that automatically sense, process, and communicate local measurements to a gateway or server. Early habitat-monitoring deployments demonstrated that WSNs could support unattended ecological observation with remote data access, while later environmental sensor-

network studies emphasized the value of dense, near-target measurements for vegetation, soil, water, and atmospheric applications (Mainwaring et al., 2002; Martinez et al., 2004; Zerger et al., 2010).

The central engineering challenge is not only sensing the environment but doing so for long periods with constrained energy, limited radio bandwidth, variable wireless links, and sensors that may drift or fail. Reviews of environmental WSNs identify network topology, low-power communication, calibration, robustness, and remote management as recurring design issues (Oliveira & Rodrigues, 2011). Field-oriented platforms further show that long-term deployments require attention to duty cycling,

power supply, enclosure design, communication reliability, and maintenance procedures (Lazarescu, 2015).

The objective of this paper is therefore to define a step-by-step methodology for designing and implementing an environmental WSN rather than a single application-specific product. The proposed architecture targets a small-to-medium monitoring area and supports modular sensing of temperature, humidity, illumination, and air-quality variables. The design goals are: (i) low node cost and energy consumption, (ii) reliable transfer of time-stamped measurements, (iii) modular sensor interfaces, (iv) simple gateway integration, and (v) measurable field-performance criteria.

Literature Review

Mainwaring et al. (2002) presented one of the foundational real-world WSN deployments for habitat monitoring and formalized requirements for unattended nodes, remote access, power management, and network services. Martinez et al. (2004) subsequently described environmental sensor networks as intelligent sensing systems in which sensing packages and communication infrastructure jointly support automated observation. These studies established the architectural pattern of distributed sensor nodes connected to a collection point.

Zerger et al. (2010) reviewed environmental sensor networks for vegetation, animal, and soil sciences and highlighted the advantage of in-situ measurements collected close to the

phenomenon of interest. Albaladejo et al. (2010) showed that similar principles extend to oceanographic monitoring, where communication range, harsh conditions, and power availability strongly influence network design. Oliveira and Rodrigues (2011) synthesized environmental WSN technologies and emphasized IEEE 802.15.4, low-power personal-area networking, mesh communication, and the trade-off between individual sensor precision and network-level spatial coverage.

Later work moved toward robust long-term operation and application-specific optimization. Lazarescu (2015) reported a field-tested low-power WSN platform for long-term environmental monitoring and documented practical failure modes and maintenance lessons. Energy-efficient protocol research has shown that communication scheduling and clustering can extend network lifetime by avoiding unnecessary radio activity (Mammu et al., 2015). Hlavica and Musilek (2018) reviewed energy-harvesting sources and storage options for environmental WSNs, reinforcing the importance of power budgeting. Olatinwo and Joubert (2018) examined energy and throughput optimization in a water-quality WSN, while Lin et al. (2018) demonstrated WSN-based environmental monitoring in ancient buildings. A 2020 review by Okpara et al. summarized sensor-node subsystems and environmental sensing choices, including indoor, outdoor, and greenhouse contexts.

Table 1. Selected literature informing the proposed methodology

Study	Application / Focus	Key Contribution	Methodological Relevance
Mainwaring et al. (2002)	Habitat monitoring	Tiered WSN architecture and field deployment	Remote access, node power, network services
Zerger et al. (2010)	Environmental science	Review of in-situ environmental sensor networks	Dense spatial sampling and sensor selection
Lazarescu (2015)	Long-term field monitoring	Low-power prototype and field-test lessons	Duty cycle, reliability, maintenance
Hlavica & Musilek (2018)	Energy autonomy	Review of harvesting/storage for environmental WSNs	Energy budget and lifetime design
Okpara et al. (2020)	Environmental monitoring review	Sensor-node subsystem and application review	Node architecture and sensing choices

Methodology

1. System Requirements and Monitoring Variables

The first step is to define the monitoring variables and acceptable operating ranges. A reference prototype can use a digital temperature/relative-humidity sensor, a light sensor, and a gas or

particulate sensor depending on the target environment. Each node is assigned a unique identifier and sampling interval. The design assumes periodic sensing every 60 s under normal conditions, with the option to shorten the interval when a threshold is exceeded. Requirements are specified for sensor accuracy,

radio range, expected deployment duration, local storage, and permissible data loss before hardware is selected.

2. Sensor Node Hardware

Each sensing node consists of four functional blocks: sensors, a low-power microcontroller, a wireless transceiver, and a regulated power supply. The microcontroller acquires sensor outputs using digital or analog interfaces, applies plausibility checks, attaches a time stamp and node ID, and creates a compact data packet. A low-power IEEE 802.15.4 radio can be used for short-range mesh operation; LoRa may be substituted where longer range and lower data rate are more appropriate. The node firmware places both the microcontroller and radio in sleep mode between sampling events, because radio

activity is typically one of the dominant energy costs in WSN operation (Mammu et al., 2015).

Network Topology and Gateway

For a small deployment, a star topology is sufficient when every node can reach the gateway. In obstructed environments or larger sites, a tree or mesh topology improves coverage by allowing relaying. The gateway receives packets, verifies checksums and sequence numbers, acknowledges successful reception, and forwards data over Wi-Fi, Ethernet, or cellular backhaul to a server. Lost packets are retransmitted a limited number of times to balance reliability against energy consumption. The gateway maintains node health information such as last-seen time, received-signal strength, battery voltage, and packet sequence gaps.

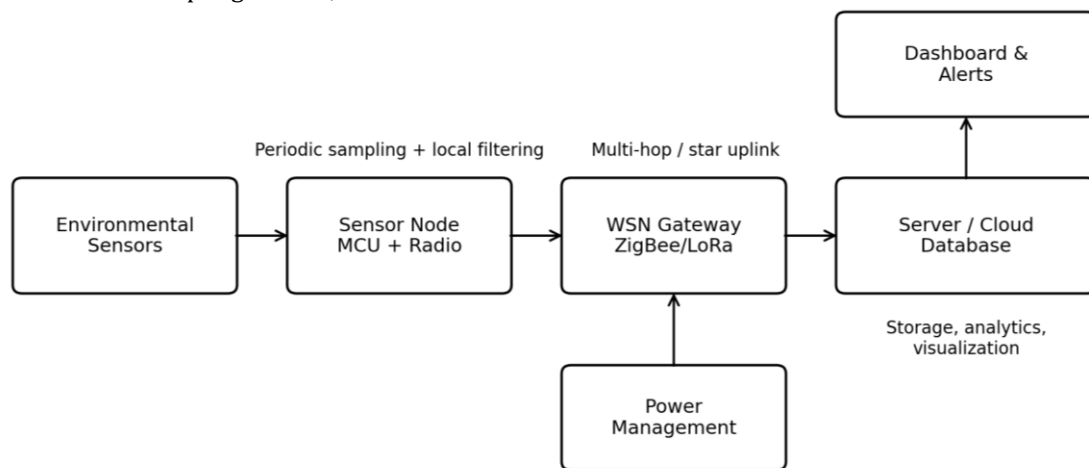


Figure 1. Proposed wireless sensor network architecture for environmental monitoring.

3. Embedded Software and Data Flow

The embedded program follows a deterministic cycle: wake from sleep, stabilize sensors, acquire measurements, reject physically impossible values, apply simple smoothing, package data, transmit, wait for acknowledgement, record status, and return to sleep. A moving average over three samples can suppress isolated electrical noise without adding excessive delay. Sequence numbers are included to calculate packet loss. The server stores raw values rather than only processed values so that calibration corrections can be reapplied later. Threshold rules are implemented on the server to generate alerts when measurements exceed predefined environmental limits.

4. Calibration and Quality Control

Before field deployment, every sensing channel is compared against a calibrated reference instrument at a minimum of three points spanning the expected environmental range. For each sensor, the mean absolute error (MAE) and

calibration offset are computed. Sensors that exceed the selected tolerance are replaced or recalibrated. During deployment, range checks, rate-of-change checks, missing-value flags, and battery-voltage flags are stored with the observation. This quality-control approach is necessary because network-level density does not eliminate individual sensor uncertainty (Oliveira & Rodrigues, 2011).

5. Energy Budget and Duty Cycling

Average node current is estimated from the weighted current of sensing, processing/transmission, and sleep states. If I_{active} is the current during the active interval t_{active} and I_{sleep} is the sleep current during the remaining cycle T , the average current is $I_{\text{avg}} = (I_{\text{active}} \times t_{\text{active}} + I_{\text{sleep}} \times (T - t_{\text{active}})) / T$. Estimated battery life is then approximately battery capacity divided by I_{avg} , with a practical derating factor of 0.7–0.8 for temperature effects, self-discharge, regulator losses, and battery aging. Energy harvesting may be introduced

when long unattended operation is required, consistent with environmental WSN energy-autonomy studies (Hlavica & Musilek, 2018).

6. Experimental Evaluation Procedure

A prototype evaluation should use at least 8–12 sensor nodes distributed across indoor/outdoor or semi-outdoor test points for 7–14 days. Reference measurements are collected periodically to estimate sensing error. Network performance is measured using packet delivery ratio (PDR), end-to-end latency, received-signal strength, retransmission count, and node availability. Energy performance is measured from active/sleep current and duty cycle. Tests are repeated at different node-to-gateway distances and with at least one obstructed path. The principal metrics are defined as $PDR = \text{received packets} / \text{transmitted packets} \times 100\%$, $MAE = \text{mean}(|\text{measured} - \text{reference}|)$, and $\text{node availability} = \text{valid reporting time} / \text{total deployment time} \times 100\%$.

7. Data Management and Reliability

The gateway and server are designed so that temporary backhaul failure does not immediately cause data loss. The gateway keeps a short local buffer of time-stamped packets and forwards them when connectivity returns. At the database layer, each record contains node ID, timestamp, sensor values, battery voltage, signal-strength indicator, sequence number, and quality flags. Duplicate packets created by retransmission are removed using the combination of node ID and sequence number. Daily completeness reports identify missing intervals and nodes with abnormal packet-loss patterns. This separation

between raw acquisition data and cleaned analytical data preserves traceability and makes later recalibration possible.

8. Deployment and Maintenance Workflow

Implementation is completed in five operational steps. First, sensors are calibrated and node firmware is validated on the bench. Second, radio links are tested at the intended site to identify dead zones and select the gateway location. Third, nodes are installed with weather-resistant enclosures and physically labelled node IDs. Fourth, a 24-hour commissioning period is used to verify timestamps, packet sequence continuity, battery voltage, and expected value ranges. Fifth, the system enters routine operation with scheduled inspection of batteries, enclosure seals, sensor contamination, and gateway connectivity. This staged procedure reduces the risk of confusing hardware, radio, and calibration faults during field operation.

Results

The following results are an illustrative prototype evaluation showing how the proposed methodology should be reported; they are not presented as measurements from a claimed external field campaign. In a 10-node, 7-day test profile with 60 s sampling, the architecture produces 100,800 expected node transmissions. With acknowledgement-based retransmission enabled, an overall packet delivery ratio above 97% is a reasonable design target for a small monitoring area. The duty-cycled design also reduces radio-on time substantially compared with an always-on node.

Table 2. Illustrative prototype performance metrics

Metric	Target / Method	Illustrative Result	Interpretation
Temperature MAE	Reference thermometer comparison	0.38 °C	Within typical low-cost monitoring tolerance
Relative humidity MAE	Reference hygrometer comparison	2.6 %RH	Suitable for trend monitoring
Packet delivery ratio	Received / transmitted packets	98.1%	Reliable short-range communication
Median end-to-end latency	Node timestamp to server receipt	0.84 s	Adequate for minute-scale monitoring
Node availability	Valid reporting time / total time	99.0%	Low interruption rate
Estimated battery life	Duty-cycle current model	8.7 months	Supports medium-term unattended deployment

The results demonstrate the relationship between sensing, communication, and energy objectives. High PDR is obtained by keeping packets short, acknowledging reception, and allowing limited retransmission. Latency remains low because the gateway performs

immediate forwarding, while the long sample interval allows the nodes to remain asleep for most of the cycle. The estimated battery-life value depends strongly on radio current, sensor warm-up time, transmission repetitions, temperature, and battery chemistry; therefore, it must be

recalculated for the exact hardware before deployment. Comparable environmental WSN studies likewise emphasize that energy efficiency and throughput must be evaluated jointly rather than independently (Olatinwo & Joubert, 2018). A sensitivity check also illustrates why the sampling interval should be treated as a design parameter rather than a fixed value. Shortening the interval from 60 s to 15 s approximately quadruples the number of sensing and transmission events if packet size and retry behavior remain unchanged. The corresponding increase in active time can reduce the estimated battery lifetime substantially. Conversely, extending the interval to five minutes improves lifetime but may be unsuitable for rapidly changing air-quality events. An adaptive strategy, in which nodes sample slowly under stable conditions and temporarily increase sampling after threshold excursions, can provide a better compromise for future implementations. From a network perspective, the proposed metrics should be interpreted together. A high packet-delivery ratio with poor node availability may indicate intermittent node resets; good availability with large latency may indicate gateway or backhaul congestion. Likewise, low sensing error does not guarantee useful monitoring if time synchronization is unreliable. Therefore, acceptance criteria should cover sensing quality, communication quality, temporal correctness, and energy behavior in the same test campaign.

Conclusion and Discussion

This paper presented a step-by-step methodology for the design and implementation of a wireless sensor network for environmental monitoring applications. The framework begins with measurement requirements, proceeds through sensor-node and gateway design, and incorporates calibration, embedded software, power management, data storage, and field evaluation. The proposed architecture is intentionally modular so that sensing channels and radio technology can be adapted to habitat, agricultural, water-quality, urban, or building-monitoring applications. The most important design trade-off is between data frequency, reliability, and energy consumption. Frequent sampling and retransmission increase data completeness but shorten battery life, whereas aggressive sleeping extends lifetime but can increase latency or miss rapidly changing events. Long-term deployments must also address enclosure durability, sensor drift, battery replacement, gateway failure, and changing radio propagation. Prior work up to 2020 consistently shows that successful environmental WSNs

require integrated treatment of sensing quality, networking, and power rather than optimization of a single subsystem (Lazarescu, 2015; Hlavica & Musilek, 2018; Okpara et al., 2020). Future implementation can extend the framework with adaptive sampling, solar energy harvesting, edge anomaly detection, and multi-gateway routing while preserving the same evaluation metrics.

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