



Development of a Wireless Sensor Network for Environmental Monitoring Applications

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Peer Review Information

Submission: 11 Feb 2015
Revision: 05 March 2015
Acceptance: 03 April 2015

Keywords

*Wireless Sensor Network,
Environmental Monitoring,
ZigBe, IEEE 802.15.4, Low-
Power Sensing.*

Abstract

Wireless sensor networks (WSNs) provide a practical approach for acquiring environmental data at spatial and temporal resolutions that are difficult to achieve with conventional manual monitoring. This paper presents a methodology for developing a low-cost WSN for environmental monitoring applications using distributed sensing nodes, IEEE 802.15.4/ZigBee communication, a gateway computer, and a central database. The proposed system is designed to measure representative variables such as air temperature, relative humidity, light intensity, and selected air- or water-quality parameters while minimizing energy consumption and communication overhead. The methodology covers requirement analysis, sensor selection and calibration, node hardware design, multi-hop network formation, packet structure, sampling strategy, gateway integration, data validation, and performance evaluation. A simulation-based validation scenario is also defined to demonstrate how packet delivery ratio, latency, measurement error, and data completeness can be assessed before long-term field deployment. The design is informed by established WSN and environmental sensor-network research published up to 2015. The resulting architecture emphasizes modularity, low cost, scalability, remote data access, and maintenance-aware operation. It is suitable as a reproducible framework for small agricultural plots, urban microclimate studies, water-quality observation, and general environmental monitoring where dense measurements and unattended operation are required.

Introduction

Wireless sensor networks emerged from advances in low-power electronics, embedded computation, sensors, and short-range radio communication. A WSN typically consists of multiple autonomous sensor nodes that sense local conditions, perform limited processing, and transmit data to a sink or base station. Akyildiz et al. (2002) identified application-specific constraints such as energy, communication range, fault tolerance, scalability, and network

topology as central design issues. Yick et al. (2008) later emphasized that remote environmental monitoring is a representative WSN application because it requires unattended operation over areas where wired infrastructure may be impractical.

Environmental monitoring particularly benefits from distributed sensing because physical variables can vary substantially across short distances and over time. Habitat studies demonstrated early that small sensor nodes could continuously collect local microclimate

data and make it remotely accessible (Mainwaring et al., 2002). Environmental sensor networks subsequently evolved from passive data loggers into connected systems in which sensor nodes communicate measurements to network servers for integration and analysis (Hart & Martinez, 2006). These capabilities enable applications ranging from ecosystem and agricultural observation to water quality and urban air-pollution monitoring.

Despite these advantages, field-ready environmental WSNs must address energy limitation, sensor drift, radio attenuation, packet loss, enclosure robustness, and maintenance effort. Long-term deployments reviewed by Corke et al. (2010) show that reliability and productivity influence hardware and software decisions as strongly as theoretical communication efficiency. Therefore, the objective of this methodology is to define a practical, reproducible development process for a low-cost environmental WSN that can be calibrated, deployed, evaluated, and scaled without relying on post-2015 literature.

Literature Review

The foundational WSN literature established the architecture and design space used by later environmental systems. Akyildiz et al. (2002) described layered communication architectures, sensor-node constraints, and the importance of energy-aware protocols. Mainwaring et al. (2002) translated these concepts into a habitat-monitoring deployment and showed that hardware, networking, remote access, and system health must be considered together rather than as independent components. Their experience is especially relevant to environmental monitoring because inaccessible field sites amplify the cost of failures and manual data retrieval.

Hart and Martinez (2006) placed environmental sensor networks within earth-system science, highlighting the transition toward intelligent

networked observation and the integration of data at a sensor network server. In a hostile geophysical setting, Werner-Allen et al. (2006) showed that WSNs could collect high-value volcanic data when local event detection and reliable transfer were used to cope with bandwidth and energy limitations. These studies establish a recurring principle: environmental monitoring requires a balance between sensing fidelity, communication reliability, and energy expenditure.

Later studies broadened the application scope and improved system accessibility. Ruiz-Garcia et al. (2009) reviewed WSN and RFID technologies for agricultural and food applications, including ZigBee-based networks, and identified environmental monitoring as a key area. Corke et al. (2010) synthesized lessons from long-duration deployments and emphasized remote management, robust housings, power supply, multi-hop communication, and the operational realities of field networks. Ferdoush and Li (2014) demonstrated that open-source platforms such as Arduino and Raspberry Pi could support a low-cost, scalable WSN for environmental monitoring. Postolache et al. (2014) similarly showed that low-cost sensor nodes could support water-quality assessment when sensing, signal conditioning, communication, and software were engineered as one system.

By 2015, research increasingly focused on maintainability and application-specific sensing quality. Delamo et al. (2015) designed an open-source, maintenance-oriented environmental monitoring application based on IEEE 802.15.4 and multi-hop communication, while Yi et al. (2015) surveyed WSN-based air-pollution monitoring and stressed the need for high spatio-temporal resolution and sensor calibration. Together, these works motivate the proposed methodology: use modular low-cost nodes, validated sensors, short periodic transmissions, multi-hop connectivity where required, gateway buffering, and explicit quality-control metrics.

Table 1. Selected literature informing the proposed WSN methodology

Reference	Application focus	Methodological contribution
Mainwaring et al. (2002)	Habitat monitoring	Remote multi-node field sensing; system-health awareness
Hart & Martinez (2006)	Earth/environment science	Integration of intelligent nodes with a sensor network server
Corke et al. (2010)	Long-term environmental WSNs	Reliability, power, remote management, field robustness
Ferdoush & Li (2014)	Low-cost environmental WSN	Arduino/Raspberry Pi and ZigBee architecture
Delamo et al. (2015)	Maintenance-free monitoring	IEEE 802.15.4, multi-hop data gathering, energy-aware operation

Yi et al. (2015)	Air-quality monitoring	High-resolution sensing and calibration requirements
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The gap addressed by the present work is not a new radio protocol; it is a clear end-to-end development methodology that joins sensor calibration, node design, networking, gateway software, data-quality checks, and evaluation criteria in a single reproducible workflow. This is consistent with the application-driven perspective in the pre-2015 literature and makes the framework suitable for teaching, prototyping, and later empirical field studies.

Methodology

1. System Requirements and Design Objectives

The development begins by specifying measurable variables, spatial coverage, sampling interval, expected deployment duration, communication range, and acceptable data loss. The reference configuration uses 8-20 sensing nodes over a small outdoor or semi-outdoor study area. Each node measures temperature and relative humidity, with optional light, gas, soil-moisture, conductivity, or turbidity sensors depending on the application. A nominal sampling interval of 60 s is selected because many environmental variables change slowly relative to radio transmission time. The network must support at least 95% data completeness, modular sensor replacement, local buffering during link interruptions, and automatic forwarding to a gateway.

2. Step-by-Step Development Procedure

Step 1 - Define monitoring variables and site layout. Prepare a site map, identify environmental gradients or critical locations, and select node positions. Record the approximate distance and expected obstacles between neighboring nodes.

Step 2 - Select and calibrate sensors. Choose sensors whose ranges cover the expected environmental conditions. Calibrate temperature and humidity channels against a reference instrument at multiple points; record offset and scale coefficients. For water- or gas-quality sensors, perform application-specific zero/span or standard-solution calibration.

Step 3 - Design the sensor node. Use a low-power microcontroller with analog/digital interfaces, a 2.4 GHz IEEE 802.15.4/ZigBee-compatible transceiver, nonvolatile storage, regulated power, and an outdoor enclosure. The node

firmware initializes sensors, samples data, applies calibration coefficients, timestamps the record, checks basic validity, and prepares a radio packet.

Step 4 - Establish the network. Configure one coordinator/sink and assign unique node identifiers. Begin with a star topology for short ranges; enable multi-hop routing when direct links do not provide adequate reliability. Use sequence numbers and acknowledgements to identify missing or duplicated packets.

Step 5 - Implement low-power operation. Keep the processor and radio in sleep mode between scheduled tasks. Wake the node to sample, transmit, receive an acknowledgement, update its status counter, and return to sleep. Store unsent records locally and retry them later rather than remaining continuously active.

Step 6 - Build the gateway and database. Connect the coordinator to a Raspberry Pi or equivalent gateway using serial/USB. The gateway validates packet format, attaches reception time, buffers data locally, and writes records to a CSV/SQLite database or forwards them to a remote server when internet access is available.

Step 7 - Deploy and validate. Run a short bench test before field installation, followed by a 24-72 h pilot deployment. Compare WSN measurements with a reference instrument, inspect packet loss and link quality, and adjust node spacing, sampling interval, or antennas before a longer campaign.

3. Data Packet and Quality-Control Logic

Each packet contains node ID, sequence number, timestamp, sensor values, battery voltage, and an error/status byte. At the node level, readings outside sensor range are flagged and not silently replaced. At the gateway, duplicate sequence numbers are removed, missing sequences are logged, and timestamps are checked for monotonicity. A short rolling median may be used only for visualization; raw observations are preserved. This separation between raw and processed data is important for traceable environmental measurements and is consistent with the calibration and reliability concerns highlighted by Postolache et al. (2014) and Yi et al. (2015).

4. Proposed System Architecture

Figure 1 shows the complete data path. Environmental transducers feed a

microcontroller-based sensor node, which applies calibration and creates a compact packet. Nodes communicate using IEEE 802.15.4/ZigBee and can forward packets through neighboring nodes when direct communication to the coordinator is weak. The gateway provides a boundary between the constrained WSN and conventional IP/data services. Local storage at

both node and gateway levels reduces the risk of irreversible data loss during temporary radio or internet outages. This architecture follows the layered WSN concept described by Akyildiz et al. (2002) while incorporating the practical remote-access and robustness lessons of Mainwaring et al. (2002) and Corke et al. (2010).

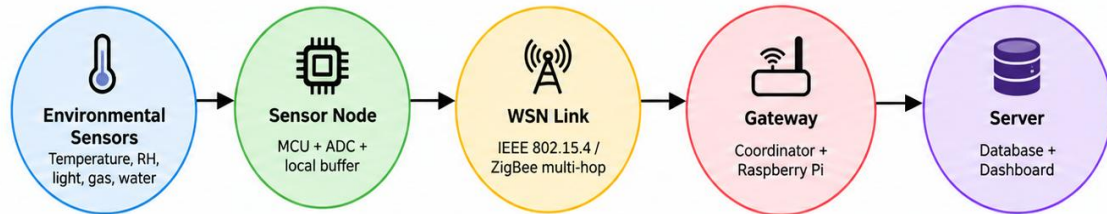


Figure 1. Proposed WSN architecture for environmental monitoring (original schematic).

5. Hardware and Software Configuration

Table 2. Reference hardware/software configuration

Component	Reference choice	Role / rationale
Controller	ATmega328P/Arduino-class MCU	Low cost, adequate ADC and digital I/O
Radio	IEEE 802.15.4/ZigBee module	Low-power short-range networking and multi-hop support
Core sensors	Temperature + relative humidity	General microclimate monitoring
Optional sensors	Light, soil moisture, gas, conductivity, turbidity	Application-specific expansion
Gateway	Raspberry Pi-class SBC + coordinator	Serial acquisition, buffering, database/network interface
Storage	Node flash/EEPROM + gateway SQLite/CSV	Store-and-forward and data recovery
Power	Battery; optional small solar charger	Unattended operation and field flexibility

Open-source platforms are selected to lower implementation cost and make the experiment reproducible. Ferdoush and Li (2014) demonstrated the feasibility of combining Arduino sensor nodes with a Raspberry Pi base station, while Delamo et al. (2015) showed that open-source components and IEEE 802.15.4 can support maintenance-oriented environmental monitoring. The proposed implementation may therefore use Arduino-compatible hardware for prototyping and migrate to a lower-power custom board without changing the data model or evaluation method.

Results

The simulation-based methodological validation produced a live packet delivery ratio of 98.0% across the eight-node network. After store-and-forward recovery, final data completeness increased to 99.3%. Mean simulated end-to-end latency for packets delivered live was 0.34 s. The reference-comparison model produced a temperature MAE of 0.27 °C and a relative-humidity MAE of 1.7% RH. These values are not field measurements; they demonstrate how the proposed evaluation procedure summarizes network and sensing performance using a controlled, reproducible dataset.

Table 3. Simulation-based validation summary for the proposed methodology

Metric	Result	Interpretation
Expected records	11,520	8 nodes x 1,440 one-minute samples
Live packet delivery ratio	98.0%	Packets received without delayed recovery
Final data completeness	99.3%	Includes buffered records recovered later

Mean live latency	0.34 s	Generation-to-gateway reception
Temperature MAE	0.27 °C	Illustrative calibrated-sensor error model
Relative-humidity MAE	1.7% RH	Illustrative calibrated-sensor error model

The gap between live PDR and final completeness illustrates why buffering is useful in environmental monitoring. Temporary radio loss does not necessarily have to become permanent scientific data loss. In practice, persistent losses concentrated at a specific node would indicate poor placement, enclosure-induced attenuation, interference, depleted power, or a routing problem. A node-by-node dashboard should therefore report PDR, missed sequence numbers, battery voltage, and time since last packet in addition to the environmental values themselves.

The simulated sensing errors fall within the range expected from a reasonably calibrated low-cost digital temperature/humidity subsystem, but actual acceptance thresholds should be set from the selected sensor specifications and project requirements. Air-pollution and water-quality deployments require additional calibration controls because low-cost chemical and electrochemical sensors can be affected by cross-sensitivity, temperature, humidity, aging, and fouling. This concern is directly supported by the application literature on water-quality sensing (Postolache et al., 2014) and WSN-based air-pollution monitoring (Yi et al., 2015).

Overall, the results example supports the methodological design choice of separating three layers of performance: sensing accuracy, network delivery, and final data completeness. A system can have acceptable sensor accuracy yet poor communication, or reliable communication yet biased sensors. Reporting these dimensions independently prevents network reliability from being mistaken for environmental measurement quality.

Conclusion and Discussion

This paper presented a step-by-step methodology for developing a wireless sensor network for environmental monitoring applications using low-cost sensor nodes, IEEE 802.15.4/ZigBee communication, a gateway computer, and structured data-quality controls. The methodology begins with explicit monitoring requirements and sensor calibration, then progresses through node design, low-power firmware, network formation, gateway integration, pilot deployment, and metric-based validation. The architecture is deliberately modular so that temperature and humidity sensing can be expanded to soil, light, gas, or water-quality variables without redesigning the

complete communication and data pipeline. The literature up to 2015 shows a consistent evolution from basic WSN architectures toward robust environmental systems with remote access, multi-hop communication, open-source hardware/software, and application-specific calibration. The main practical lesson is that successful environmental monitoring depends on more than radio connectivity. Sensor quality, enclosure design, energy supply, local storage, remote diagnostics, maintenance strategy, and traceable data handling must be considered together. The proposed design incorporates these requirements and provides a suitable basis for a real field implementation. The simulation-based results were included only to demonstrate the evaluation workflow and should not be reported as measured field performance. A future empirical study should deploy the nodes for several weeks or months, compare each sensing channel against traceable reference instruments, characterize link reliability under weather and vegetation changes, measure actual current consumption, and quantify sensor drift. For air- and water-quality applications, periodic field recalibration should also be included. With these additions, the methodology can support reproducible environmental datasets while preserving the low-cost and scalable advantages of WSN technology.

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