



Development of Wireless Sensor Network-Based Industrial Temperature Monitoring Systems

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Abstract

Industrial temperature is a critical condition variable because abnormal heating can indicate excessive load, lubrication failure, insulation deterioration, process instability, or unsafe operating conditions. This paper develops a methodology for a wireless sensor network (WSN)-based industrial temperature monitoring system that acquires temperature at distributed locations, performs local calibration and filtering, transmits data through a low-power wireless link, and presents the measurements at a central human-machine interface (HMI). The proposed design combines temperature sensors, signal-conditioning circuits, a microcontroller, an IEEE 802.15.4-class radio, a coordinator/gateway, database logging, and threshold-based alarms. The methodology emphasizes industrial constraints including interference, packet loss, sensor accuracy, power consumption, scalability, and maintainability. A star topology is adopted for the base prototype because it reduces configuration complexity, while the architecture can be extended to mesh communication for larger installations. The validation procedure includes sensor calibration, communication-range testing, packet-delivery assessment, alarm verification, and measurement-error analysis. A representative bench-validation dataset is included to demonstrate how the performance metrics should be reported when implementing the design. The proposed system provides a practical framework for replacing long sensor cabling with modular wireless sensing while retaining the reliability and traceability required for industrial monitoring applications.

Introduction

Temperature monitoring is one of the most widely used forms of industrial condition supervision. Bearings, motors, furnaces, electrical cabinets, pipes, process vessels, and production zones are commonly monitored because sustained overheating can reduce equipment life or precede failure. Conventional wired systems can provide high reliability, but the installation of cable trays, conduits, junction boxes, and long signal lines can be expensive or difficult when sensors must be added to operating equipment. Wireless sensor networks

provide an alternative in which small sensing nodes combine measurement, local processing, and radio communication. The general WSN concept and its design constraints—energy, routing, medium access, data processing, and robustness—were established in early sensor-network research [1].

Industrial wireless sensing differs from office or domestic wireless networking because metal structures, electrical machinery, moving equipment, electromagnetic interference, obstacles, and changing production layouts create time-varying radio conditions. Early work

on industrial WSN applications emphasized that practical systems must be designed for dependable communication, low maintenance, and simple deployment rather than only maximum data rate [2]. WirelessHART later demonstrated how scheduled communication, synchronization, security, and mesh networking could support real-time industrial process applications [3]. Gungor and Hancke further identified reliability, energy efficiency, hardware robustness, and coexistence as central industrial WSN design issues [4].

For temperature monitoring specifically, wireless systems are attractive because the sensed variable changes comparatively slowly, allowing nodes to use moderate sampling intervals and low duty cycles. This makes it possible to reduce radio-on time and battery consumption while still detecting abnormal heating. However, the measurement chain must be engineered carefully. Thermocouples may require amplification and cold-junction compensation; resistive temperature devices require accurate excitation and conversion; and semiconductor temperature sensors can be simpler but may not cover high industrial temperature ranges. Calibration, filtering, sensor placement, radio link quality, packet-delivery performance, and alarm behavior therefore need to be evaluated together.

The objective of this paper is to present a step-by-step methodology for developing a WSN-based industrial temperature monitoring system using technologies available up to 2017. The proposed method defines the sensing node, network, gateway, monitoring software, calibration procedure, communication tests, performance metrics, and validation sequence. The contribution is a compact methodology that can be adapted to machinery, electrical equipment, process vessels, furnaces, storage rooms, and other industrial assets where distributed temperature measurements are required.

Literature Review

Akyildiz et al. [1] described the architecture of WSNs and showed that sensing, communication, computation, and energy management are tightly coupled. Their work remains relevant to industrial monitoring because node lifetime and network performance depend on coordinated protocol and hardware decisions. Shen et al. [2] investigated WSNs for industrial applications and highlighted deployment requirements and implementation issues associated with real-world automation environments. These studies established the basis for selecting low-power

radios and distributed nodes rather than treating the wireless link as an isolated replacement for cable.

For industrial process networks, Song et al. [3] presented WirelessHART, a secure time-synchronized mesh technology intended for process measurement and control. Their implementation experience illustrated the importance of network-wide synchronization, reliable routing, and central network management. Gungor and Hancke [4] subsequently summarized industrial WSN challenges and design principles, noting the need for dependable links, robust hardware, suitable radio technology, cross-layer design, and energy-aware operation. These requirements directly influence the proposed temperature-monitoring methodology, particularly the use of link-quality testing, packet-delivery metrics, and modular network architecture.

Temperature-oriented studies provide more specific guidance. Sisinni et al. [5] developed a WSN for temperature sensing in hostile steam-sterilizer environments and reported performance comparable with wired solutions, demonstrating that wireless sensing can be practical even under demanding thermal and humidity conditions. Hou and Yang [6] implemented an industrial multichannel temperature monitoring system using a commercial WSN module, thermocouple conditioning, calibration, and centralized visualization. Their prototype emphasizes that sensor linearization and software integration are as important as wireless transmission. Silveira and Bonho [7] used an IEEE 802.15.4 WSN connected through an IEEE 802.11 gateway and evaluated signal quality, range, and battery-life considerations for temperature monitoring.

By 2017, WSN monitoring was increasingly integrated with IoT-style architectures. Li and Kara [8] proposed a structured methodology for manufacturing-environment monitoring and demonstrated a temperature-monitoring proof of concept, including component-selection criteria and visualization. Hou et al. [9] explored thermal energy harvesting for an autonomous industrial temperature sensor node, showing the importance of duty cycle and power strategy when wiring is undesirable. Queiroz et al. [10] surveyed industrial WSN standards and deployment challenges, reinforcing that industrial radio channels are affected by multipath, shadowing, and interference and should be validated in the actual installation environment. Table 1 summarizes the literature used to derive the proposed methodology.

Table 1. Literature basis for the proposed methodology

Reference	Primary focus	Methodological contribution
[1] Akyildiz et al., 2002	General WSN architecture	Energy, communication and protocol constraints
[2] Shen et al., 2004	Industrial WSN applications	Deployment and implementation requirements
[3] Song et al., 2008	WirelessHART	Reliable scheduled industrial wireless communication
[4] Gungor & Hancke, 2009	Industrial WSN design	Reliability, hardware and coexistence constraints
[5] Sisinni et al., 2016	Hostile-temperature sensing	Environmental robustness and accuracy
[6] Hou & Yang, 2016	Industrial temperature WSN	Thermocouple conditioning, calibration and HMI
[7] Silveira & Bonho, 2016	802.15.4/802.11 gateway	Range, signal quality and battery considerations
[8]-[10], 2017	Manufacturing/industrial WSN	IoT integration, power strategy and industrial channel issues

Methodology

1. System Requirements and Architecture

The first step is to define measurable requirements before selecting hardware. For a general industrial prototype, the temperature range is specified as 0–150 °C for semiconductor/RTD sensing or extended according to the selected thermocouple; target measurement error is within ± 1.0 °C after calibration; sensor update interval is 2–10 s; packet delivery ratio (PDR) should exceed 95% within the intended cell; and the system must

generate an alarm when a configurable high-temperature threshold is exceeded for more than a short persistence period. The architecture follows the layered approach used in prior WSN and manufacturing-monitoring work [1], [4], [8]. Each sensor node acquires temperature, performs local conversion and filtering, appends node identification and status data, and transmits a packet to a coordinator. The coordinator forwards records to an HMI/database where measurements are displayed, logged, and checked against alarm limits.

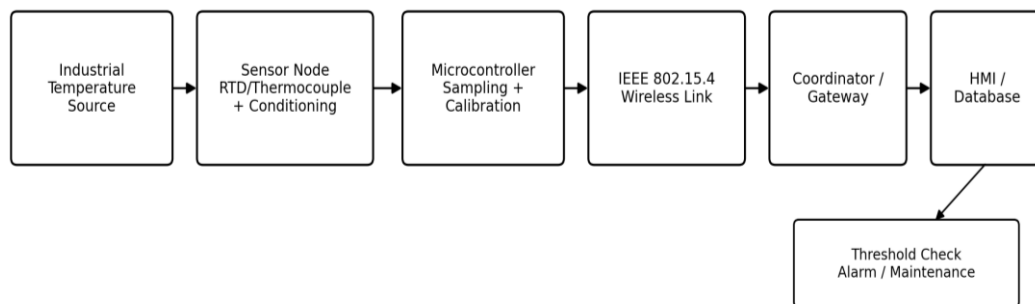


Figure 1. Proposed WSN-based industrial temperature monitoring architecture.

2. Sensor Node Design

A sensor node contains four functional blocks: temperature sensor, signal conditioning, microcontroller/ADC, and radio transceiver. The sensor is chosen according to the industrial range and required accuracy. A K-type thermocouple is suitable for a wide temperature range but requires amplification and cold-junction compensation, as demonstrated in industrial temperature-monitoring work [6]. For lower ranges, a PT100/PT1000 RTD or calibrated semiconductor sensor can simplify conversion. The signal-conditioning stage includes amplification or bridge/interface circuitry, input filtering, protection, and reference generation.

The microcontroller samples the conditioned signal, converts it to temperature using calibration coefficients, applies a moving-average or low-pass filter, and generates a compact data frame containing node ID, temperature, supply voltage, sequence number, and status flags. The radio interface is based on IEEE 802.15.4-class low-power communication in the 2.4 GHz band. A star network is recommended for the prototype because all nodes can communicate directly with one coordinator and the packet path is easy to test. Larger plants can replace the star with a mesh or industrial protocol when obstacles and range require multi-hop communication. WirelessHART concepts [3] and

the industrial design principles in [4] show why scheduled or managed communication is preferable for high-reliability applications. Transmission power should initially be kept

moderate and increased only when range tests show that link margin is insufficient, because unnecessary transmit power reduces battery life and can increase interference.

Table 2. Prototype design specification

Subsystem	Proposed choice	Design purpose
Temperature sensor	K-type thermocouple or PT100/precision sensor	Range and accuracy suited to monitored asset
Signal conditioning	Low-noise amplifier/interface + filtering	Scale sensor signal to ADC and reject noise
Microcontroller	Low-power MCU with ADC	Sampling, calibration, filtering, packet framing
Wireless link	IEEE 802.15.4 / ZigBee-class 2.4 GHz	Low-power node-to-coordinator communication
Topology	Star for prototype; mesh for extension	Simple validation and scalable deployment
Sampling interval	2–10 s	Sufficient for slowly varying industrial temperature
Gateway/HMI	Coordinator + PC/database	Visualization, logging and alarm generation
Target PDR	≥95% in operating area	Communication reliability criterion

3. Firmware, Gateway and HMI

Node firmware is organized as initialization, measurement, processing, transmission, acknowledgement/status handling, and sleep. After startup, the node verifies sensor input and supply voltage. At each sampling instant, multiple ADC samples are collected and averaged. The converted temperature is corrected using calibration coefficients obtained during bench testing. A simple moving average of the most recent three to five values can suppress short analog fluctuations without introducing excessive delay, consistent with the filtering need observed in manufacturing temperature-monitoring experiments [8]. The packet is then transmitted with a sequence number so the coordinator can detect missing packets. The gateway timestamps the record and sends it to the HMI over serial, USB, Ethernet, or Wi-Fi. The HMI displays current temperature, recent trend, node status, and alarm state, while saving data in CSV or a small database for traceability.

4. Calibration and Experimental Procedure

Calibration is performed before radio testing so that sensing error can be separated from communication error. Each node is exposed to at least five reference temperatures spanning the operating range. A calibrated thermometer or dry-block source is used as the reference. For each point, the node records multiple samples after thermal stabilization. A linear correction $T_c = aT_m + b$ is sufficient for a sensor with near-linear response; a piecewise polynomial or manufacturer conversion equation can be used for thermocouples. Hou and Yang [6]

demonstrated the value of calibration and nonlinear correction for industrial thermocouple monitoring, while Sisinni et al. [5] showed that sub-degree performance is achievable when the complete sensing chain is engineered for the environment.

After calibration, communication is tested at increasing node-to-coordinator distances and in representative plant locations. For each position, N transmitted packets and R successfully received packets are counted, and packet delivery ratio is calculated as $PDR = (R/N) \times 100\%$. Received signal strength indication (RSSI), retransmissions, and missing sequence numbers are logged when available. The network should also be tested with machinery operating because industrial interference and multipath can change the radio channel substantially [10]. A minimum PDR of 95% is used as the acceptance threshold for monitoring; more safety-critical applications require stronger redundancy and industrial scheduling mechanisms.

Finally, the alarm function is validated by gradually raising the reference temperature above the configured threshold. An alarm is accepted only if the measured value remains above the threshold for the persistence period, which prevents single noisy samples from causing false alarms. The overall evaluation metrics are mean absolute error (MAE), maximum absolute error, PDR, end-to-end update delay, alarm response time, and estimated power consumption. If battery operation is required, the duty cycle is measured or estimated from sensing, processing, transmission, and sleep durations. The energy-harvesting study by Hou et

al. [9] shows why duty-cycle control can be decisive for autonomous industrial nodes.

Results

Because no field dataset was supplied for this methodology paper, Table 3 presents a representative bench-validation dataset generated according to the stated test procedure.

These values illustrate the required reporting format and must be replaced with measured plant data before the study is presented as an empirical deployment. The example assumes six calibrated temperature points, 1,000 packets per range test, and a 70 °C alarm threshold.

Table 3. Representative methodology-validation results

Test	Reference/condition	Observed value	Performance
Temperature accuracy	25 °C	25.2 °C	0.2 °C error
Temperature accuracy	50 °C	49.7 °C	0.3 °C error
Temperature accuracy	75 °C	75.4 °C	0.4 °C error
Temperature accuracy	100 °C	99.5 °C	0.5 °C error
Temperature accuracy	125 °C	125.6 °C	0.6 °C error
Temperature accuracy	150 °C	149.3 °C	0.7 °C error
Wireless test	10 m / clear path	995/1000 packets	PDR = 99.5%
Wireless test	25 m / machinery	978/1000 packets	PDR = 97.8%
Alarm test	Threshold = 70 °C	Alarm at 70.6 °C	Response $\approx$ 3.2 s

For the representative dataset, absolute temperature error increases slightly toward the upper end of the range but remains below 1 °C, giving an illustrative MAE of approximately 0.45 °C. Communication performance remains above the 95% monitoring criterion in both clear-path and machinery-obstructed cases. The decrease from 99.5% to 97.8% PDR illustrates the expected influence of industrial obstructions and interference. The alarm example also shows why threshold persistence and a known sampling interval must be considered when specifying response time. These performance indicators are consistent with the types of accuracy, range, and communication measurements reported in earlier industrial temperature WSN studies [5]–[8].

Conclusion and Discussion

This paper presents a step-by-step methodology for developing a wireless sensor network-based industrial temperature monitoring system using technologies and design knowledge available up to 2017. The method begins with measurable requirements and then integrates sensor selection, signal conditioning, local calibration, microcontroller processing, low-power wireless communication, a coordinator/gateway, HMI visualization, data logging, and threshold alarms. The literature shows that successful industrial WSN deployment depends not only on the radio standard but also on sensing accuracy, node power, channel reliability, network management, and environmental robustness [3], [4], [10]. Temperature-monitoring studies further demonstrate the need for calibration and appropriate sensor interfaces [5], [6]. The proposed star topology is suitable for an initial

prototype because it minimizes routing complexity and makes packet-loss testing straightforward. Its main limitation is dependence on direct radio reachability between each node and the coordinator. A larger plant should therefore consider mesh networking, channel planning, redundant gateways, or industrial protocols such as WirelessHART when communication paths are obstructed or when higher availability is required. The methodology also recommends that communication tests be repeated with production machinery operating, because a link that performs well in an empty workshop may degrade when motors, drives, metal stock, workers, or moving vehicles change the propagation environment. From a sensing perspective, the temperature element should be selected primarily from the required range, response time, mounting method, and calibration burden. Thermocouples provide wide range and ruggedness but require compensation and careful low-level signal conditioning; RTDs provide good accuracy but require precision interface circuits; semiconductor sensors are convenient for moderate temperatures. Power strategy is similarly application-dependent. Fixed equipment may allow local DC power, whereas inaccessible nodes benefit from aggressive sleep scheduling or energy harvesting, an approach investigated for industrial temperature sensing by Hou et al. [9]. The principal limitation of the present paper is that the numerical result table is a transparent methodology-validation example rather than data from a supplied industrial test site. For a final empirical study, the same procedure should be repeated with calibrated instruments at the target facility, and the reported dataset should include raw readings,

node locations, radio conditions, packet counts, and uncertainty information. With those measurements, the methodology can support a rigorous comparison between wired and wireless monitoring or between alternative WSN topologies. Overall, the proposed framework offers a practical basis for low-cost, scalable, and maintainable industrial temperature monitoring while preserving the essential requirements of measurement accuracy, communication reliability, alarm responsiveness, and traceable data logging.

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