



Performance Analysis Of Wireless Sensor Networks for Industrial Monitoring Applications

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Abstract

Wireless sensor networks (WSNs) provide a flexible means of collecting temperature, vibration, pressure, current and other condition-monitoring data in industrial plants where cable installation is expensive or impractical. Their performance, however, is strongly affected by radio propagation, metallic obstructions, interference, routing depth and the energy constraints of sensor nodes. This paper presents a methodology for evaluating an industrial WSN using four principal indicators: packet delivery ratio (PDR), end-to-end delay, throughput and energy consumed per generated packet. A 30-node multi-hop monitoring network is modeled in a 2.4 GHz industrial environment, with low, moderate and high interference conditions. The evaluation procedure combines a controlled traffic model, probabilistic per-hop transmission, one retransmission opportunity and energy accounting for transmission, reception, processing and sensing. The resulting simulation shows a progressive degradation as interference increases: PDR declines from approximately 99.2% under low interference to 85.6% under high interference, while average delay and energy expenditure rise. The findings reinforce the industrial design principles reported in pre-2018 literature: dependable monitoring requires robust link margins, channel-aware operation, bounded retransmissions, careful routing and traffic engineering. The paper therefore offers a concise and reproducible framework for comparing WSN configurations before deployment in harsh industrial facilities.

Introduction

Industrial plants depend on timely condition information to identify abnormal temperature, vibration, pressure, flow, electrical current and machine-state changes. Traditional wired instrumentation is reliable, but installation and reconfiguration can be costly in rotating equipment, large production halls and geographically dispersed assets. WSNs replace part of this cabling with autonomous sensing nodes that perform local acquisition and wireless communication. The general WSN concept, including its resource constraints and

application-driven design requirements, was established by Akyildiz et al. (2002) and later reviewed comprehensively by Yick et al. (2008). Industrial use is more demanding than many office or environmental deployments. Metallic structures produce multipath propagation, shadowing and abrupt channel variation; electromagnetic equipment and co-located radios add interference; and monitoring traffic may have explicit deadlines. Measurements by Tanghe et al. (2008) demonstrated that industrial indoor propagation exhibits substantial large-scale and temporal fading. Consequently,

industrial WSN design must consider not only coverage but also reliability, bounded delay, network lifetime and the effects of retransmission.

Industrial wireless sensor networks (IWSNs) offer self-organization, rapid deployment and flexible reconfiguration, but these advantages do not eliminate the need for predictable service. Gungor and Hancke (2009) identified reliability, energy efficiency, real-time behavior, security and suitable protocol architectures as major design challenges. Flammini et al. (2009) similarly emphasized that industrial sensing differs from conventional data networking because relatively small packets may require cyclic and time-constrained delivery. This paper therefore focuses on measurable network behavior rather than on sensing accuracy alone. The objective is to develop and demonstrate a step-by-step methodology for performance analysis of a WSN intended for industrial monitoring. The study asks three practical questions: (1) how does increasing interference affect successful packet delivery; (2) what penalty is paid in delay and node energy when retransmissions are required; and (3) which design parameters should be adjusted before field deployment? The analysis is intentionally limited to monitoring traffic, where data flows primarily from sensors toward a gateway, rather than closed-loop actuation requiring stricter deterministic guarantees.

Literature Review

Early WSN research established that network architecture and protocol selection are shaped by energy, hardware, topology and application requirements (Akyildiz et al., 2002). Shen, Wang, and Sun (2004) specifically examined industrial applications and highlighted the need to align sensor-network design with automation requirements. Yick et al. (2008) later organized WSN challenges across platform, protocol-stack and deployment dimensions, providing a useful foundation for choosing performance indicators. For industrial environments, radio-channel behavior is central. Tanghe et al. (2008) found industrial indoor path loss and temporal fading to be strongly influenced by local topography and reflective structures. Cheffena (2012) subsequently evaluated industrial WSN channel models and IEEE 802.15.4 performance, illustrating why a generic free-space assumption is insufficient for realistic planning. These studies support the inclusion of variable link success probabilities in a performance methodology. Protocol-level work has addressed the reliability and timing limitations of basic contention-based access. Zand et al. (2012) reviewed

WirelessHART, ISA100.11a and related industrial approaches and concluded that industrial monitoring and control impose stringent real-time and reliability requirements. Remke and Wu (2013) modeled WirelessHART link failures and evaluated end-to-end delay and reachability, showing that route quality and failure probability directly affect performance. Nobre, Silva, and Guedes (2015) also used simulation to evaluate WirelessHART reliability, energy consumption and the effect of error probabilities.

At the IEEE 802.15.4 level, Du, Navarro, and Mieveville (2015) evaluated packet delivery, latency and energy consumption under different industrial traffic conditions. Sheng et al. (2015) emphasized efficient resource management for IWSNs integrated with IoT systems. Finally, Queiroz et al. (2017) systematically mapped industrial WSN research and highlighted persistent challenges from interference, shadowing, multipath fading, non-stationary channels and standard-specific mechanisms. Collectively, the literature suggests that a useful industrial performance study should jointly assess reliability, timeliness, throughput and energy rather than optimizing a single metric.

Methodology

Step 1: Define the Industrial Monitoring Scenario
A representative monitoring cell is modeled as a 50 m × 30 m industrial area containing 29 sensing nodes and one gateway. Sensors represent machine-mounted temperature, vibration, pressure or current monitors. Data are generated periodically and forwarded through a multi-hop mesh toward the gateway. The communication band is 2.4 GHz, consistent with common IEEE 802.15.4-based industrial systems. The mesh assumption reflects the need to route around machinery and obstructions rather than requiring every sensor to communicate directly with the gateway.

Step 2: Establish the Network Architecture
The architecture contains four functional layers: sensing, multi-hop communication, gateway aggregation and supervisory monitoring. Sensor nodes acquire measurements and form packets; relay nodes forward traffic; the gateway time-stamps and aggregates received packets; and the monitoring station stores trends and produces alarms. Figure 1 summarizes the analysis path used in this study.

Step 3: Set Simulation Parameters and Assumptions

A controlled Monte Carlo packet-level model is used so that the effect of interference can be isolated. Each sensing node generates one 64-byte payload per second for a 600 s observation period. Paths are two to five hops, with most

packets using approximately three hops. Every hop is allowed one retransmission. Rather than claiming a site-specific propagation model, three per-attempt link-success probabilities are used to represent low, moderate and high impairment

conditions. This abstraction follows the literature evidence that industrial fading and interference cause large temporal changes in link quality (Tanghe et al., 2008; Queiroz et al., 2017).

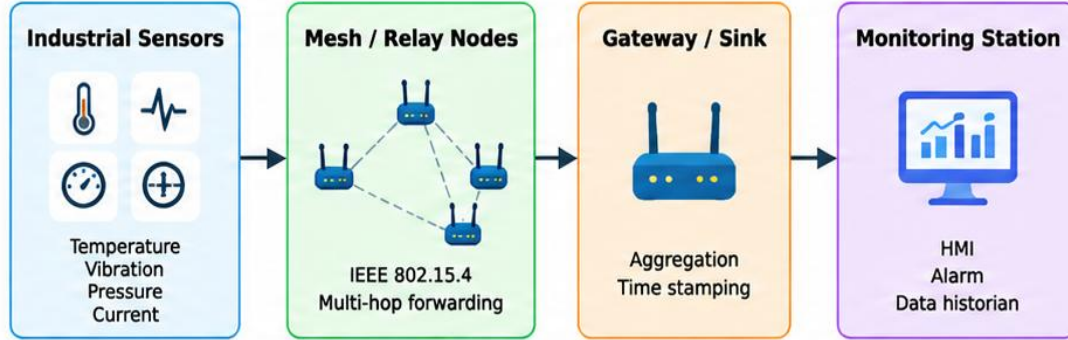


Figure 1. Proposed industrial WSN monitoring and performance-analysis architecture.

Table 1. Simulation configuration for the proposed performance study.

Parameter	Value	Rationale
Network size	30 nodes (29 sensors + 1 gateway)	Small/medium industrial monitoring cell
Area	50 m × 30 m	Representative plant-floor zone
Payload / period	64 bytes / 1 s	Periodic condition-monitoring traffic
Observation time	600 s	17,400 generated sensor packets
Path length	2–5 hops	Mesh routing around obstructions
Retransmission limit	1 per hop	Controls delay and energy cost
Link-success probability	0.95 / 0.88 / 0.78	Low / moderate / high interference

Step 4: Define Performance Metrics

Four metrics are calculated. Packet delivery ratio is the percentage of generated packets that reach the gateway: $PDR = (N_{received} / N_{generated}) \times 100$. End-to-end delay is the mean time from packet generation until successful gateway reception, including per-hop transmission, queue/backoff time and retransmission penalty. Throughput is the successfully delivered payload in bits divided by the 600 s observation interval. Energy per generated packet includes sensing/processing plus the modeled transmit and receive/listen energy consumed along the traversed route.

These metrics were chosen because they correspond to the main industrial performance concerns described by Gungor and Hancke (2009), Zand et al. (2012), Du et al. (2015), and Nobre et al. (2015). PDR indicates dependability; delay indicates timeliness; throughput indicates useful network capacity; and energy per packet provides a direct proxy for battery-life pressure. The metrics should be interpreted together, because aggressive retransmission can improve PDR while increasing latency and energy consumption.

Step 5: Execute the Experiments

For each interference condition, the random-number generator is initialized with a fixed seed to make the experiment repeatable. A packet is assigned a route length, then each hop attempts transmission. If the first attempt fails, one retry is permitted; if both attempts fail on any hop, the packet is considered lost. Successful and failed attempts both consume energy and time. This mechanism deliberately captures the basic trade-off that occurs in industrial links: deteriorating channel quality leads to more retries, which increases both delay and energy before the packet is either delivered or discarded.

The study uses 17,400 generated packets per interference condition (29 sensors × 600 packet intervals). Results are aggregated over the complete interval, reducing the influence of individual random events. Because the objective is methodological demonstration rather than certification of a commercial standard, the numerical outputs are reported as controlled simulation results and should not be treated as field measurements. A real deployment should replace the abstract link-success probabilities with measured RSSI/LQI, packet-error

distributions, channel occupancy and topology-specific routing statistics.

Step 6: Interpretation Criteria

For non-critical condition monitoring, a useful engineering target is high delivery reliability with delay comfortably below the sampling interval. The exact acceptance thresholds should be selected by the plant owner according to the monitored process and alarm criticality. In this methodology, relative change across interference conditions is more important than a universal threshold: a large PDR drop, rapidly rising delay, or steep increase in energy per packet indicates insufficient link margin, excessive hop count,

congested channel access or an inadequate retransmission policy.

Results

Table 2 summarizes the output of the controlled simulation. Performance is strongest in the low-interference case. Under moderate interference, reliability remains high but the network spends more time and energy on retransmissions. Under high interference, the delivery ratio falls substantially and both delay and energy increase, demonstrating that a network that appears acceptable under clean-channel tests may perform differently on an active industrial floor.

Table 2. Simulated WSN performance under three industrial interference conditions.

Condition	PDR (%)	Avg. delay (ms)	Throughput (kb/s)	Energy / packet (mJ)
Low interference	99.22	40.7	14.73	5.10
Moderate interference	95.49	45.8	14.18	5.36
High interference	85.57	51.3	12.71	5.55

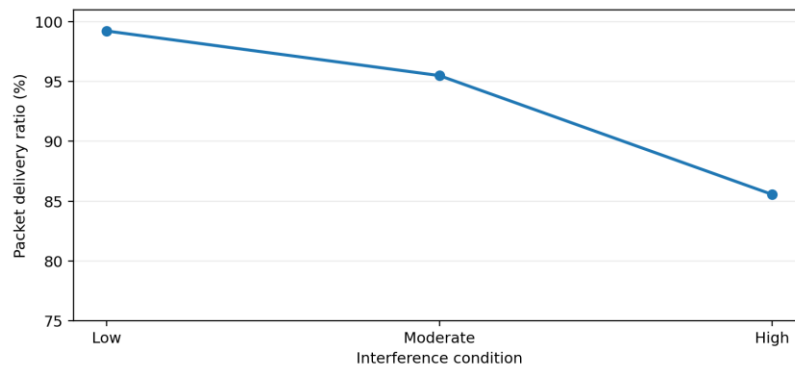


Figure 2. Packet delivery ratio degradation as interference increases (simulation results).

The low-interference case achieved a PDR of 99.22% and an average end-to-end delay of 40.7 ms. The result indicates that a short multi-hop route with a strong per-attempt link probability and a single retry can deliver nearly all monitoring packets without excessive timing cost. This behavior is consistent with the design objective of industrial mesh systems described by Zand et al. (2012) and with the use of redundancy/retransmission mechanisms analyzed in WirelessHART studies (Remke & Wu, 2013; Nobre et al., 2015).

Under moderate interference, PDR decreased to 95.49% while average delay rose to 45.8 ms and energy expenditure increased to 5.36 mJ per generated packet. This is an important operating region because the network may still appear reliable at the application layer, yet additional retries consume energy and reduce the margin

available for traffic bursts. Du et al. (2015) likewise showed that industrial IEEE 802.15.4 performance must be assessed jointly in terms of packet delivery, latency and energy rather than from connectivity alone.

The high-interference condition produced the clearest degradation, with PDR of 85.57%, average delay of 51.3 ms and energy use of 5.55 mJ per generated packet. The reduction in useful throughput follows directly from the lost payload, while failed attempts still consume radio energy. This trend matches the broader finding that industrial channels are vulnerable to interference, multipath effects and non-stationary behavior (Tanghe et al., 2008; Queiroz et al., 2017).

The results also illustrate why simply increasing the retry limit is not always the best remedy. More retries can recover some packets but also

increase queue occupancy, end-to-end latency and energy use. In larger networks, this can create additional contention and secondary losses. A more effective engineering response may combine channel selection or hopping, alternate routing, reduced hop count, careful placement of relay nodes and traffic prioritization. These mechanisms are consistent with the industrial networking approaches surveyed by Gungor and Hancke (2009), Zand et al. (2012), and Sheng et al. (2015).

Conclusion and Discussion

This methodology demonstrates a compact way to evaluate WSN suitability for industrial monitoring before hardware deployment. The proposed workflow begins with a clearly defined monitoring scenario, maps the end-to-end data path, establishes traffic and impairment assumptions, measures PDR, delay, throughput and energy, and compares those metrics across controlled interference conditions. The simulated results confirm the expected trade-off: as link quality degrades, successful delivery falls while retransmission-related delay and energy increase. For practical deployment, the principal implication is that coverage alone is an inadequate acceptance criterion. A sensor can remain technically connected while its packet-delivery reliability or delay becomes unsuitable for useful monitoring. Industrial commissioning should therefore include repeated packet-level tests during different production states, particularly when motors, welders, conveyors, Wi-Fi networks or moving metallic objects are active. The radio environment characterized in industrial-channel studies (Tanghe et al., 2008; Cheffena, 2012) makes this temporal testing especially important. The methodology is also suitable for comparing alternatives. For example, an engineer can repeat the experiment with a different gateway position, additional relay nodes, changed sampling periods, more or fewer retransmissions, different route-selection rules or multiple frequency channels. The preferred design is not necessarily the configuration with the highest PDR; it is the configuration that satisfies application reliability and delay requirements with acceptable energy cost. This multi-objective view aligns with prior industrial WSN studies that jointly consider reliability, real-time performance, energy efficiency and resource management (Gungor & Hancke, 2009; Nobre et al., 2015; Sheng et al., 2015). The study has three limitations. First, the link-success probabilities are abstract representations of industrial impairment rather than measurements from a specific factory. Second, the energy model is simplified and does not include a particular radio

transceiver's sleep-state current, startup current or battery chemistry. Third, the traffic model is periodic and does not include synchronized alarm bursts. These limitations are deliberate to keep the method transparent and reproducible. For a site-specific research study, the next step is to collect channel and traffic traces, calibrate the simulation model, and validate the predicted PDR and delay against a physical testbed. Within these limits, the paper provides a practical performance-analysis framework grounded in literature available through 2017. It can be used as a baseline methodology for industrial temperature, vibration, electrical, pressure and condition-monitoring applications, and can be extended to WirelessHART, ISA100.11a or IEEE 802.15.4e systems by replacing the simplified MAC and retransmission model with the scheduling and channel-hopping behavior of the target standard.

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